OPTIMIZING REINJECTION STRATEGY IN PALINPINON, PHILIPPINES BASED ON CHLORIDE DATA

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By
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I certify that I have read this report and that in my opinion it is fully adequate, in scope and in quality, as partial fulfillment of the degree of Master of Science in Petroleum Engineering.

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Abstract

One of the guidelines established for the safe and efficient management of the Palinpinon Geothermal Field is to adopt a production and reinjection strategy such that the rapid rate and magnitude of reinjection fluid returns leading to premature thermal breakthrough would be minimized, if not avoided. To help achieve this goal, sodium fluorescein and radioactive tracer tests have been conducted to determine the rate and extent of communication between the reinjection and producing sectors of the field. The first objective of this work was to examine how the results of these tests, together with information on field geometry and operating conditions could be used in algorithms developed in Operations Research and modified by James Lovekin to allocate production rates among the Palinpinon wells.

Due to operational and economic constraints, however, such tracer tests were very limited in scope and number. This prevents obtaining explicit information on the interaction between each injection and producing well. Hence, there was a need to look for another parameter which can be used for this purpose. The second objective of this work was, therefore, to investigate how the reservoir chloride value of the producing well and the injection rate of the injection well could be used to provide a ranking of the injection/production pair of wells and, thereby, aid in optimizing the reinjection strategy of the field.

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Ph.D. DISSERTATIONS

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Section 1

Introduction

This study aimed at finding ways of optimizing the production and well utilization scheme at the Palinpinon-I Geothermal steamfield. In a geothermal field exploitation, the main objective is to provide a balance between obtaining maximum productivity from the wells and, at the same time, prolonging the economic life of the reservoir. Presently, the developer relies on a variety of ways ranging from experimental methods to numerical simulation to help ensure that the field is being managed safely and efficiently. Depending on field response, appropriate development strategies and field management policies are instituted and modified.

The Palinpinon Geothermal Field is one of two producing steamfields currently operated by the Philippine National Oil Company (PNOC). Even in the early stages of drilling, the importance of injection to dispose of wastewater while maintaining reservoir pressures has been recognized. Hence, the steam requirement of the 112.5 MWe commercial plant, known as Palinpinon-I, is met by 21 production wells and 10 reinjection wells drilled as deep and as far away as possible from the producing wells. The production wells produce from multiple feed zones and discharge two-phase fluid from a liquid-dominated reservoir.

Being a variable load power station, Palinpinon-I was operated at low loads during the first few years of operation as the transmission lines and distribution system for the Negros Island were being completed. As a result, production and reinjection wells were utilized intermittently, affordingadequate surface and well testing exercises which showed the fast response of the field to exploitation. One of the more significant changes observed was the general trend of increasing reservoir chloride among the producing wells. This has been attributed mainly to the rapid returns of reinjection fluids to the producing sector (Harper and Jordan, 1985). Apprehensive of the negative effects of rapid reinjection returns, such **as** premature thermal degradation of producing wells, developers implemented guidelines for the safe and efficient management of the Palinpinon reservoir. One of these is adoption of a production and reinjection well utilization strategy, under any given load demand, such that the rapid rate and magnitude of reinjection fluid returns would be minimized, if not avoided. Presently, decisions on well utilization schemes have been arrived at, on a relative basis, by the confluence of production and reinjection fluid chemistry, downhole measurements of pressure and temperature, interference testing **,** tracer testing, and the interpreted field model.

The necessity of providing a tool to optimize the well utilization strategy has served as the primary motivation for this work. To achieve this goal, the problem has to be posed as an optimization problem. Firstly, this means defining the set of independent variables or parameters and the *constraints* which are the conditions or restrictions that limit the acceptable values of the variables. Secondly, this necessitates forming an *objective function* related in some way to the variables. The solution of the optimization problem is a set of allowed values of the variables for which the objective function, after *maximizing* or *minimizing* assumes the "optimal" value. Finally, to solve the formulated optimization problem, algorithms should be selected and modified. This has been the approach taken by James Lovekin **(1987)** in his work where injection scheduling in geothermal fields was optimized using tracer data. Flowrates are the variables subject to well and field operating conditions, and the fieldwide breakthrough index has been defined **as** the objective function.

This work applied the algorithms developed and modified by James Lovekin to the Palinpinon-I tracer return data, along with field geometry and well/field constraints. However, since Palinpinon tracer tests were limited in scope and number, an exhaustive producer/injector interaction can not be obtained. There was a need, therefore, to find another parameter that could be used to relate producer to injector for use in the optimization algorithms. It was natural to turn to reservoir chloride as one such parameter since chloride had always been used to infer the extent and magnitude of reinjection returns to the producing sector from the injection wells. Four different methods were tested to determine the degree of correlation or the strength of the relationship between the chloride value of a producing well and the flowrate of an injection well. The first three calculate the correlation between a particular producer/injector pair of wells at any given time, while the last method expresses the chloride value of a producer as a linear combination of the flowrates of the all the injection wells in service for the particular time interval considered.

Following this brief introduction, the second section of this report discusses previous work along this line of geothermal field optimization. A brief discussion of the Palinpinon Geothermal Field is given in the third section. The methods and results of optimization strategy using linear and quadratic programming are presented in the fourth section. The fifth section describes and applies the different methods of using chloride to obtain producer/injector coefficients of correlation. Finally, the last section summarizes the conclusions from this study and suggests methods of improvement.

Section 2

Previous Work

To date, the author is cognizant of only the work of James Lovekin **(1987)** along the line of geothermal optimization. In his study, Lovekin has made an exhaustive search of literature to determine what has been done to study the effects of injection in geothermal fields. Though the two usual approaches to this problem are analytical and numerical modeling of the reservoirs, these are hampered by the inherent difficulty of contructing realistic models due to fracturing and non-isothermal conditions in the reservoir. Therefore, developers turn to the more powerful and practical method of tracer testing to determine the behavior of injected fluid.

In his work, Lovekin made use of these available tracer return data to correlate the tracer results with the potential for thermal breakthrough. The underlying foundation is the simplicity with which the reservoir is idealized **as** a network of arcs connecting each pair of wells, and associating with each pair of wells an index which gives a measure of the magnitude of the flow of fluid from one well to another. Hence, by defining a function that is to be minimized, the problem has been transposed into one of optimization.

This study applies the results of Lovekin's to see how the Palinpinon-I would allocate production and injection rates on the basis of tracer test results. However, as Lovekin has demonstrated, the program works best when there is explicit information that relates every pair of wells. Since this is not true for the Palinpinon case, a method has to be found that would express the strength of relationship between producer and injector and be used in the optimization routines. This is where the study departs from Lovekin's work.

Section 3

The Palinpinon-I Geothermal Field

The Palinpinon Field (Figure **3.1)** and the Baslay de Dauin field are the two geothermal fields comprising the Southern Negros Geothermal Project. The Palinpinon field is situated roughly **15 kms.** west of the coastal city of Dumaguete, the provincial government of Negros Oriental. It is divided into two sectors — the Puhagan sector in the east and Nasuji/Sogongon in the west. The Puhagan sector, which is the concern of this study, has the first large plant, Palinpinon-I, with a generating capacity of **112.5** MWe while the Nasuji/Sogongon sector has been alloted for the proposed development of Palinpinon-11.

3.1 Brief Description of Palinpinon-I

Palinpinon-I is one of two steamfields currently operated by the Philippine National Oil Company (PNOC). The power station, unlike most other geothermal power stations, was designed and constructed to operate as a variable load station. Due to the hostile topography of the area, a compact development scheme consisting of four multi-well production pads and three multi-well injection pads was effected. Figure **3.2** shows the steam gathering system, the well pads, as well as the well tracks.

Eighteen (18) of the twenty-one (21) production wells were drilled directionally to intersect structures which were believed to be zones of high permeability. These wells, drilled to depths ranging from 2774 mMD (measured depth) to 3467 mMD produce from multiple zones and discharge two-phase fluid from a single-phase reservoir.

The need to reinject waste liquid effluent has been primarily dictated by environmental constraint, which in the Philippines prohibits full disposal into the rivers being used for ricefield irrigation. In addition, the benefits of maintaining reservoir pressures and increasing thermal recovery through reinjection have been recognized. The ten (10) reinjection wells which accept waste liquid by gravity flow, were drilled to the eastern, northern, and western sections of the sector. They have been drilled as deep and as far as possible, at the periphery of the field identified to be the outflow region of the reservoir.

Shortly after commissioning of the Palinpinon-I power plant in June 1983, initial observations of the reservoir response and performance of both production and reinjection well showed significant changes. One of these was the increasing trend of reservoir chloride for the production wells (Figure 3.3). This has been interpreted (Harper and Jordan, 1985) as evidence of the rapid return of reinjected fluids to the producing sector, and in some cases, to localized pressure drawdown. Since this could lead to premature thermal breakthrough of cooler injected fluids at producing wells, and cut short the economic life of the field, guidelines for the safe and efficient management of the Palinpinon reservoir have been established. These include the requirements of

- minimizing fluid residence times in the surface and downhole piping while operating reinjection wells at or near maximum capacity,
- minimizing steam wastages brought about by varying steam demand and supply, and
- adopting a production and reinjection well utilization strategy such that the rapid rate and magnitude of reinjection fluid returns leading to premature thermal breakthrough would be minimized, if not avoided.

The first of these requirements is the solution to the problem of silica deposition which would occur by gravity injection of a fluid that is supersaturated with respect to amorphous silica. The second requirement which is economical in nature, has been satisfied by prioritizing high enthalpy production wells for peaking steam requirements and choosing injection wells with additional capacity. Presently, decisions on well utilization schemes have been arrived at, on a relative basis, by the confluence of production and reinjection fluid chemistry, downhole measurements of pressure and temperature, interference testing, tracer testing, and the interpreted field model. This study attempts to provide another tool to identify fast injection paths, and aid in optimizing the well utilization strategy.

3.2 Tracer Testing in Palinpinon-I

To determine the rate and extent of communication between a reinjection well (or sector), and the producing area, tracer tests were conducted in Palinpinon-I. These tests and the results are shown in Table 3.1.

3.2.1 Sodium Fluorescein Tracer Tests

The first chemical tracer tests used the organic dye sodium fluorescein, which was introduced in July 1983 to investigate the interconnection between OK-12RD and PN-6RD. Direct connection between the two was confirmed by visual inspection of the fluid sample just 1.5 hours after injection.

In August 1984, a year after commercial operation began, the chemical dye was used on a larger scale to determine interaction of well PN-1RD with the production sector. Sixteen (16) of the production wells were monitored but positive return of the tracer (detected through UV light spectrophotometer) was confirmed only for the central Puhagan wells PN-26, PN-28, OK-7, as well as at OK-2. Arrival times ranged from 40 to 90 hours – equivalent to breakthrough velocities of 5.6 to 16.5 m/hr. Tracer return in other wells could not be ascertained due to interference of degraded by-products of sodium fluorescein with the viewing process.

Another year later, in August 1985, a greater amount of the dye was injected in PN-9RD as a precursor to the radioactive tracer testing. The test aimed to define communication between the western injection sector and the producing area. In a day's time, the dye was seen in OK-7 produced fluid. Arrival times for wells PN-17D, PN-19D, PN-26, PN-28, PN-29D and PN-31D ranged from 5.5 to 6.0 days, while for the more distant production wells PN-16D, PN-23D, and PN-SOD, first appearance of the chemical tracer occured in 7.5 to 9.8 days.

3.2.2 Radioactive Tracer

The radioactive tracer Iodine-131 (I 131) was used to be able to detect even minute returns of the injected tracer.

The first radioactive tracer was conducted in August 1981 to investigate movement of fluid injected into a shallow well to adjacent but much deeper wells. The miniscule return discounted any large direct connection between OK-2 and the adjacent wells.

In August 1983, the OK-12RD radioactive tracer test confirmed direct communication between the eastern injection well OK-12RD and the eastern production wells PN-17D, PN-15D, PN-21D, and OK-1OD in addition to the central Puhagan wells OK-7, PN-28, and PN-26. Estimated total return was 17% with mean transit times of 4 to 15 days. These translate to average aerial flow velocities of 1.7 to 4.6 m/hr. Still, the result indicates that a greater portion of the injected fluid was dispersed away from the producing sector.

Shortly after monitoring of the sodium fluorescein dye in PN-9RD, a four-fold increase of 1-131 was injected into PN-9RD. The result affirmed the fast and strong returns to OK-7 with breakthrough time of a day, mean transit time of 5.7 days, and tracer recovery of approximately 30%. The mean transit time is the time it takes for half of the tracer return to reach the production well. The rest of the production wells had tracer returns of 0.4% to 7% and average transit times of 10.3 to 16.0 days. The total tracer recovery of 45% indicates that more reinjection fluid was now returning to the producing block than had been the case before commercial operation. It affirmed the backtracking of injected fluid from the western injection sector to the central, western and southwestern producting areas.

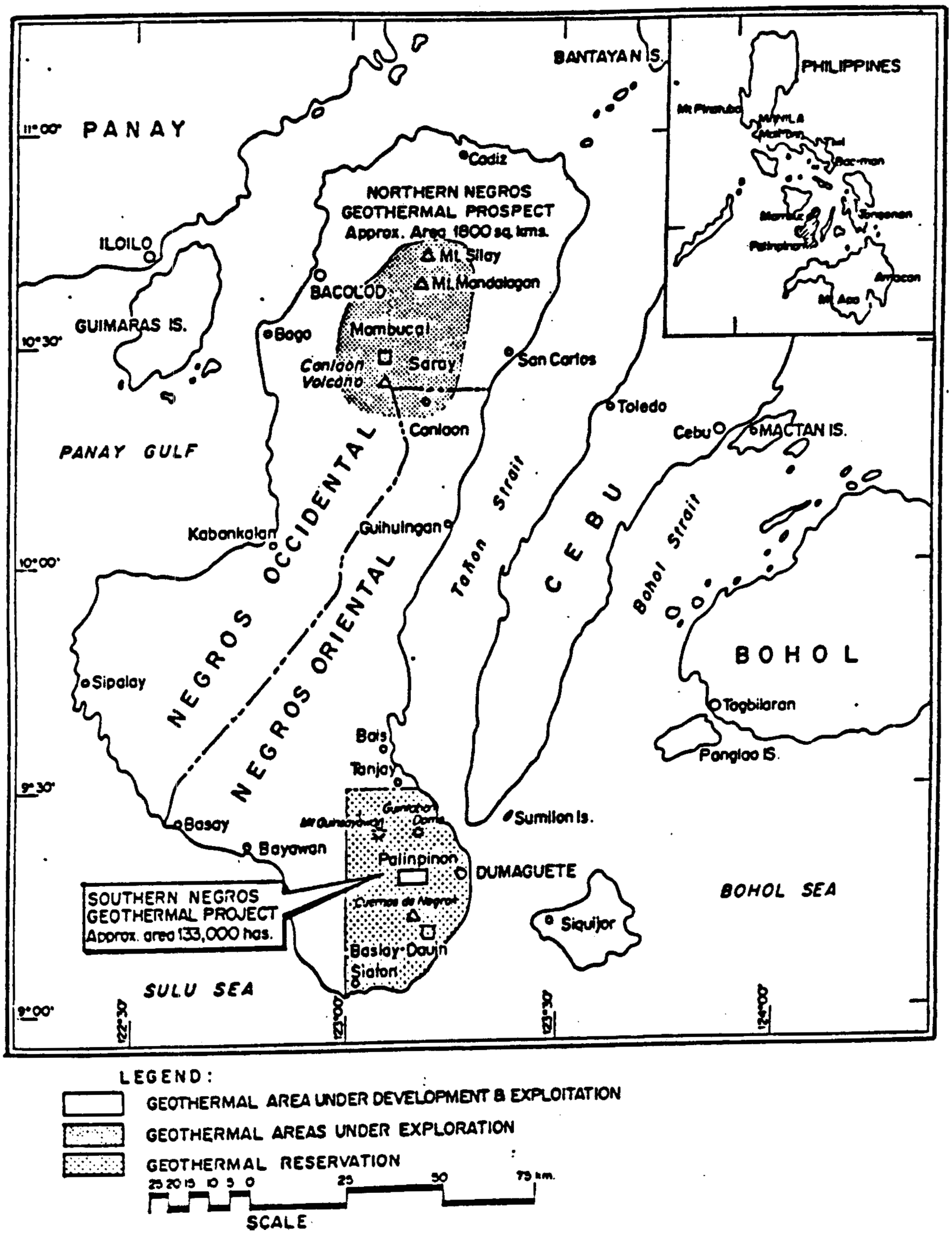


Figure **3.1: Location map** of the **Palinpinon** Geothermal Field

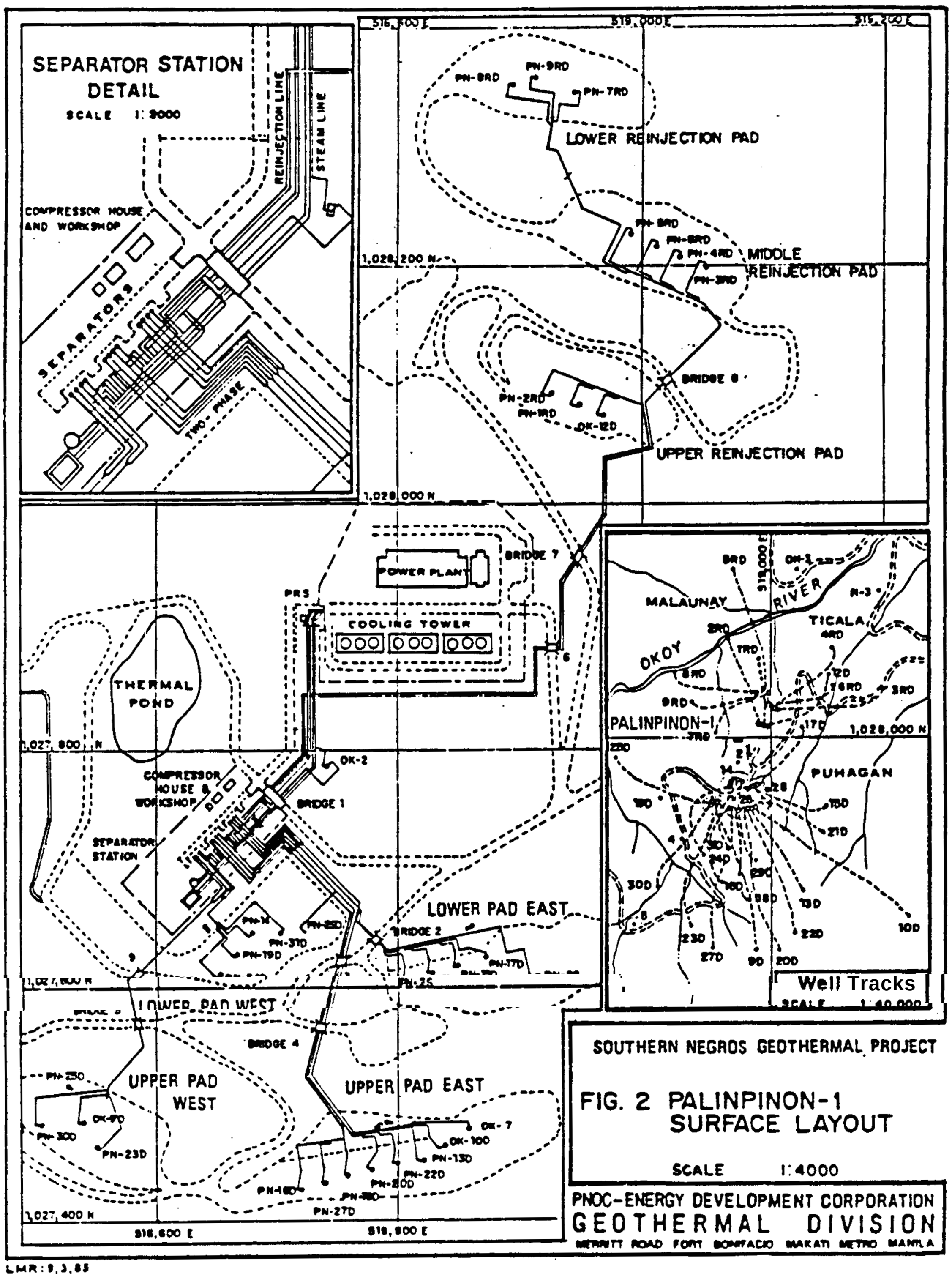


Figure 3.2: Palinpinon-I surface layout

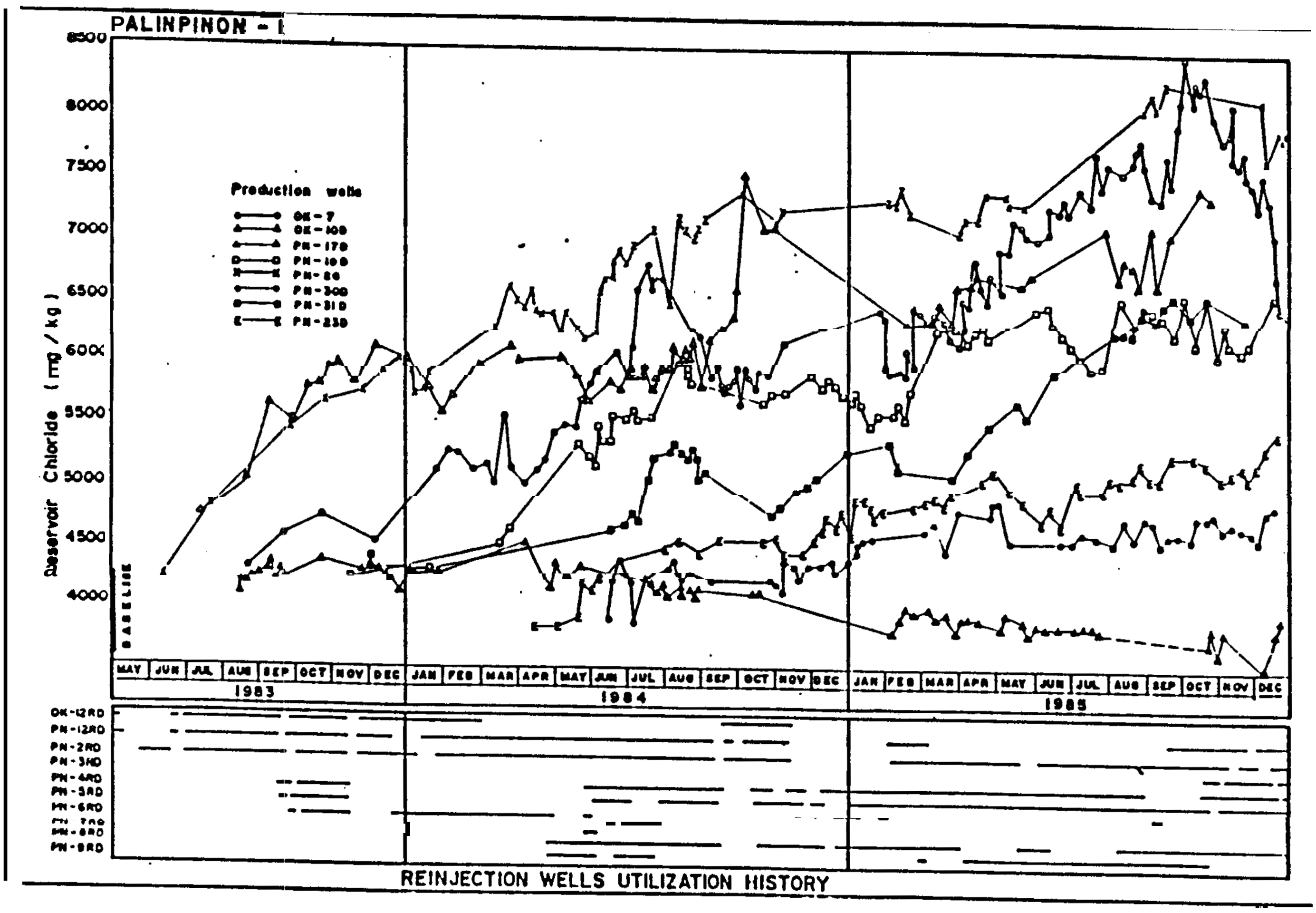


Figure **3.3:** Reservoir chloride vs time

Table **3.1: Tracer** tests in **Palinpinon** Geothermal Field

TRACER AMOUNT	RECIPIENT WELL (Inclusive Dates)	MONITORING WELLS, SPRINGS, RIVERS	RESULTS Positive Return	Transit Time	% Return
Iodine-131, 18.5 GBq (0.50 Ci)	OK-2 (15 Aug - 06 Sept 81)	OK-7, OK-12D, PN-13D PN-16D, OK-9D, OK-10D Ticala and Buhayan Springs	OK-7	16.0 days	0.23
			OK-12D	16.4 days	0.05
			PN-13D	16.2 days	0.10
Sodium Fluorescein 0.5 kg/test	OK-12RD (30 July - 02 Aug 83)	PN-6RD at different operating conditions	PN-6RD	.75-2.1 hours	8 - 55
Iodine-131, 20.2 GBq (0.545 Ci)	OK-12RD (03 Aug - 29 Aug 83)	OK-7, OK-10D, PN-15D, PN-17D, PN-21D, PN-26, PN-28, PN-29D, PN-3RD, PN-4RD, PN-6RD	OK-7	14.6 days	1.28
			OK-10D	13.8 days	1.35
			PN-15D	7.3 days	0.35
			PN-17D	3.9 days	8.22
				7.5 days	2.32
				10.5 days	2.52
			PN-28	6.0 days	0.58
			PN-21D	Traces on 4th and 9th day after tracer injection	
			PN-26	Traces on 5th and 7th day after tracer injection	
			PN-3RD	Very low traces	
			PN-4RD	Very low traces	
Sodium Fluorescein 2.0 kg	PN-1RD (28 Aug - 21 Sept 84)	OK-7, OK-9D, OK-10D, PN-15D, PN-16D, PN-17D, PN-18D, PN-19D, PN-23D, PN-24D, PN-29D, PN-30D, PN-31D, N-3, OK-2, RI 317/318, PN-3RD, PN-6RD, PN-9RD	PN-26	40.0 hours	
			PN-28	60.0 hours	
			OK-7	80.0 hours	
			OK-2	90.0 hours	
			PN-3RD	On downhole sample 27 hours after tracer injection	
			PN-6RD	On down hole sample 94 and 146 hours after injection	
			PN-9RD	On down hole sample 168 hours after injection	
Sodium fluorescein 10 kg Iodine-131, 67 GBq (1.81 Ci)	PN-9RD (26 Sept - 20 Oct 85)	OK-7, OK-9D, PN-16D, PN-17D, PN-18D, PN-19D, PN-23D, PN-26, PN-28, PN-29D, PN-30D, PN-31D RI 317/318	OK-7	5.7 days	29.20, 21.7*
			PN-29D	14.0 days	6.80 7.9
			PN-26	11.0 days	3.90, 0.5
			PN-28	11.3 days	1.10 0.4
			PN-18D	15.6 days	0.80, 1.6
			PN-30D	15.7 days	0.80 -
			PN-23D	15.8 days	0.40 -
			PN-31D	16.0 days	0.40, 1.6
			PN-16D	Tracer found in samples after 8-19 days	
			PN-19D	Tracer found in samples after 15-19 days	

*PNOC-EDC recalculated returns are in second column. Previous values for PN-26 and PN-28 believed to be erroneous due to innacurate flowrates used.

Section 4

Optimization Strategy

The results of the two tracer tests, together with field geometry, and field operating conditions were used to test algorithms developed and modified by James Lovekin **(1987)** to allocate production rates among the Palinpinon wells. This section gives a brief discussion on the fundamentals of the methods used to optimize reinjection and production rates. The reader is referred to Lovekin **(1987)** for a more thorough discussion of the algorithms and the differences between the programs used for each method.

The optimization strategy is analogous to the classical transportation problem, where a set of factories supplies a set of stores. The problem is to determine the optimum distribution scheme for the goods using the various routes or arcs such that the total transportation cost is minimized and the constraints of factory capacity, as well as store requirements are satisfied. In the geothermal analogy, the factories are the injection wells and the stores are the producers. The geothermal reservoir is idealized as a network of arcs between every pair of well where each arc is presupposed to have some potential for thermal breakthrough caused by the flow of fluid from injector to producer (Figure **4.1).**

This increased chance of thermal breakthrough is measured by the arc cost, c_{ij}, and the product of the arc cost with the well's injection rate, q_{ri}, is defined as the injector/producer pair breakthrough index, b_{ij}. The sum of an injector's arc costs over all the producing wells is its *cost coefficient*, and the sum of the breakthrough

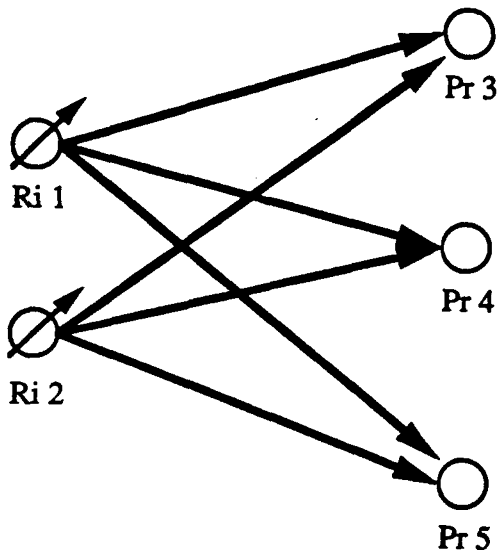


Figure 4.1: Idealized network of arcs.

indices for all arcs or well pairs is the fieldwide breakthrough index ***B***. It is this function that is to be minimized for the two approaches used.

4.1 Arc Costs

As defined above, the arc cost, c_{ij}, expresses the chance of thermal breakthrough for an injector/producer pair. It is comprised, therefore, of parameters or weighting factors, which may demonstrate a direct or inverse relationship with the likelihood of thermal breakthrough.

The weighting factors used for the arc cost by Lovekin (1987) were obtained from three sources: tracer tests, field geometry, and operating conditions. The relationship between the arc cost and each factor is shown by Equation 4.1 below.

$$c = \left[\frac{1}{t_i} \frac{1}{t_p} C_p f \frac{1}{L^2} e^{bh} \frac{q_p}{q_{pt}} \frac{1}{q_{rt}} \right] \tag{4.1}$$

This equation is intended to represent the relative effects of the various parameters - in actual use, the parameters do not necessarily **all** appear in the arc cost. This choice of which parameters to use will be site specific.

When the arc costs for all arcs connecting a certain injector i to producing wells is summed (N_2), the total is termed the *cost coefficient.* This is best illustrated by the following equation:

$$B = \sum_{i=1}^{N_1}\sum_{j=1}^{N_2} c_{ij} q_{ri} = \sum_{i=1}^{N_1} [c_{i1} + c_{i2} + \cdots + c_{iN_2}]\, q_{ri} \tag{4.2}$$

$$\textit{cost coefficient of injector } i = \sum_{j=1}^{N_2} c_{ij} = [c_{i1} + c_{i2} + \ldots + c_{iN_2}] \tag{4.3}$$

From Equation 4.1, the slug-type tracer factors which are inversely related to the arc cost are the initial tracer response t_i, and the peak tracer response t_p. The tracer test results in Palinpinon-I (Table 3.1) have demonstrated that the smaller or faster the tracer breakthrough, the greater the likelihood for thermal breakthrough between the pair of wells. The fluorescein and radioactive testing demonstrated immediate breakthrough for wells PN-26 and OK-7 which were the first wells to exhibit thermal drawdown due to reinjection returns. In contrast, it can also be seen that the greater the fractional tracer recovery f and the peak tracer concentration C_p, the higher is the chance of thermal breakthrough. Hence these two factors appear as being positively correlated to the arc cost.

Under field geometry, the two parameters which are readily available are the horizontal distance between wells L, and the difference in elevation between the permeable zones of the wells h. It is intuitive that the farther the injector from the producer, the smaller the likelihood of thermal breakthrough. However, this is reasonable only for porous-media type of reservoirs with radial flow since the surface area which can be utilized for heat transfer to the injected fluid is proportional to the square of L. Accordingly, L^2, is made inversely proportional to the arc cost. On the other hand, tracer tests from other fields such as New Zealand (McCabe, 1983) demonstrates the positive relationship between tracer breakthrough and deep producing fields. The inherent effect is for injected fluid to sink into the reservoir since it is much cooler and more dense than reservoir fluid. Consequently, one expects a greater chance of thermal breakthrough between a deep producing well and a given injection well than a shallow producing well and the same injection well. However, since h may be positive or negative depending on whether the producing zone is below or above the injection zone, it is not suitable as a weighting factor. The elevation difference h is considered positive when the producing zone is below the injecting zone. To be used as a weighting factor, Lovekin (1987) included h as an ,exponential function e^{sh}, with a scaling factor s to prevent the exponential term from dominating the rest of the weighting factors. This report maintains the **0.001** value for s to keep the weighting factor within the range of **0.37** to **2.72** for elevation differences on the order of hundreds of meters (Lovekin, **1987).**

Flow rates for production and injection wells during the tracer tests (q_{pt} and q_{rt}) can also be included as weighting factors. **A** well producing at a low rate with a positive return can be expected to encounter earlier breakthrough than another well producing at a higher rate with similar returns. Such is the case for **PN-26** during the PN-9RD tracer test. The actual tracer return to **PN-26** is only about 0.5 since it was on heavy bleed during the tracer testing. This value is comparable to the returns (0.8 - 0.4) from the other wells (Table **3.1)** which were producing at higher rates. Consequently, it is to be expected that had **PN-26** been producing at a higher rate during tracer testing q_{rt}, then its tracer returns would be much higher, indicative of an an earlier breakthrough. Subsequent field experience has proven that this is so. The same reasoning would apply to the injection rate q_{rt}. Therefore, these parameters enter as reciprocals in the calculation for arc cost.

In Equation **4.1,** the producing rate under operating conditions q_p has been entered as a weighting factor with linear relationship to the arc cost. Ideally, higher production rates cause greater pressure drawdown and increase the likelihood of thermal breakthrough. The inclusion of the producing rates under operating conditions as weighting factors rather than decision variables is based on the assumption that these rates are predetermined based on total production requirements. If this is not the case, and q_p is a decision variable, the ratio q_p/q_{pt} can be viewed as being proportional to the breakthrough index b. When the injection rate under operating conditions q_r, is a decision variable, then the ratio q_r/q_{rt} can be regarded in a similar manner. The greater these ratios are, the higher the possibilities for thermal breakthrough.

It is to be emphasized again that all these weighting factors need not be used to calculate the arc cost. Likewise, the combination of these factors is not intended to be exhaustive. Other weighting factors that the developer may deem as or more important on the basis of reservoir information and behaviour can be and should be included. Finally, appropriate weights or scaling factors could be affixed to the other arc cost components as well.

4.2 Linear Programming

A linear programming problem is a mathematical program in which the objective function is linear in the unknowns and the constraints consist of linear equalities and inequalities (Luenberger, 1984).

4.2.1 Transportation Problem

In the transportation problem, it is desired to ship quantities $a_1, a_2, \ldots, a_i$, respectively of a certain product or goods from each of i factories and received in amounts $b_1, b_2, \ldots, b_j$, respectively, at each of j destinations or stores. Associated with the transporting of a unit of product from origin or factory i to destination or store j is a unit transportation cost, c_{ij}. It is desired to determine the amounts x_{ij} to be shipped between each factory-store pair $i = 1, 2, \ldots, N_1$; $j = 1, 2, \ldots, N_2$; so as to satisfy the shipping requirements and minimize the total cost of transportation, C. Hence, the formulation of the transportation problem is given by Equation 4.4.

Minimize

$$C = \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} c_{ij} x_{ij} \tag{4.4}$$

Subject to

$$\begin{aligned}
\sum_{j=1}^{N_2} x_{ij} &\leq a_i, & i &= 1, N_1 \\
\sum_{i=1}^{N_1} x_{ij} &= b_j, & j &= 1, N_2 \\
x_{ij} &\geq 0, & &\text{for all } i, j
\end{aligned}$$

As seen in Equation 4.4 and its constraints, the classic transportation problem satisfy the requirements of a linear programming problem which is then solved, usually, by an algorithm such as the Simplex method. As a start, in the optimization problem, the decision variables are the injection rates because it was assumed that production rates had been determined beforehand.

4.2.2 Injection Optimization Problem

The formulation of the injection optimization problem is given by Equation 4.5 below.

Minimize

$$B = \sum_{i=1}^{N_1}\sum_{j=1}^{N_2} b_{ij} = \sum_{i=1}^{N_1}\sum_{j=1}^{N_2} c_{ij} q_{ri} \tag{4.5}$$

Subject to

$$q_{ri} \leq q_{rimax}, \qquad i = 1, N_1$$

$$\sum_{i=1}^{N_1} q_{ri} = Q_{rtot}$$

$$q_{ri} \geq 0$$

The injection optimization problem has the following features which demonstrate its resemblance to the transportation problem.

1. The decision variables, q_{ri} are the injection rates for each injection well **i** instead of the amount of goods transported from factory i to store **j**.
2. The arc costs, c_{ij}, expressing the chance of thermal breakthrough for each injector/producer arc or flow path replace the transportation costs per unit of goods shipped.
3. The objective function to be minimized is the fieldwide breakthrough index in place of the total transportation cost.
4. The supply constraint for a factory is now supplanted by the requirement that each injector should operate at a rate less than its capacity, q_{rimax}.

5. The demand constraint for a store is now denoted by the requirement that the summation of all injection rates be equal to the specified fieldwide total injection rate, Q_{rtot}. And,

6. The non-negativity constraint requiring that goods be shipped only from factory to store, correspond to demanding that the injectors not act as producers by operating at a "negative rate".

Although the preceding discussion outlines the similarity between the transportation problem and the injection optimization problem, there exists differences between the two.

1. While the transportation problem solves for the amount of goods shipped *across each arc,* the optimization problem solves for injection rates *ut each injection well.* Hence, the first is arc-specific while the latter is well-specific. This is natural since the geothermal developer does not have direct control over the paths of injected fluids.

2. Whereas the supply constraint in the transportation problem requires that the total of ,goods supplied by a factory i be less than or equal to its capacity, there is no need to sum the reinjection rates into each injection well in the optimization problem since the rate already delineates all flows away from the well.

3. While the demand constraint in the transportation problem requires that the sum of goods received by store j be greater than or equal to its demand, this constraint in the optimization problem is dictated, rather, by the total injection rate demanded of the field as perceived by the developer.

4. Although the transportation problem demands a material balance between the amount of goods shipped and received, there is no such requirement between the sum of injection rates and the sum of production rates. After all, as the developer decides, reinjected fluid can be part of or greater than production.

In his study, Lovekin (1987) developed four computer programs to allocate injection rates among pre-chosen injectors. The first three programs use a linear programming solver called ZXOLP from the IMSL library (IMSL, 1982), while the fourth one employs a quadratic programming solver called QPSOL developed by the Department of Operations Research at Stanford University. **A** comparative analysis of the programs reveals that the the third of the linear programming programs (LPAL3) and the quadratic programming program come close to simulating actual field situations in that they take into account the mutual dependence of injection and production rates in determining the likelihood of thermal breakthrough. Therefore, this study used these two programs in applying the Palinpinon-I case. The linear programming approach shall be referred to simply as LPAL, and the quadratic programming approach as QPAL. **A** brief summary of the programs is given after the description of the formulations.

4.2.3 LPAL Optimization

The linear programming formulation (LPAL) is a two step procedure given by Equations **4.6** and **4.7.** For the flowcharts, the source codes and the data-entry programs, the reader is :referred to Lovekin (1987).

A. Minimize

$$B_1 = \sum_{i=1}^{N_1}\sum_{j=1}^{N_2} c_{ij} q_{ri} \tag{4.6}$$

Subject to

$$q_{ri} \leq q_{rimax}, \qquad i = 1, N_1$$

$$\sum q_{ri} = Q_{rtot}$$

$$q_{ri} \geq 0$$

where c_{ij} includes q_{pj}–term from previous producer iteration.

B. Minimize

$$B_2 = \sum_{i=1}^{N_1}\sum_{j=1}^{N_2} c_{ij} q_{pj} \tag{4.7}$$

Subject to

$$q_{pj} \leq q_{pjmax}, \qquad j = 1, N_2$$

$$\sum q_{pj} \geq Q_{ptot}$$

$$q_{pj} \geq 0$$

where c_{ij} includes q_{pj}–term from previous injector iteration.

The main features and flow of this algorithm are:

- Initially, the developer inputs the number of producers and injectors, their names as wells as their maximum injection and production rates, the weighting factors considered, and finally, the number of iterations allowed for convergence.
- From the weighting factors, the arc costs and cost coefficients are computed. If no arc-specific weighting factor (such as tracer parameters, elevation change or distance) has been included, the program terminates.
- The program then solves for both production and injection rates in an alternating fashion. That is, the production rates are used as weighting factors in the allocation of injection rates in the next alteration, and vice-versa. This has been done to preserve the linearity of the objective function and permit solution by linear programming. The iteration procedure continues until convergence is achieved and successive rate allocations match.
- The program reduces production well flowrates and allows wells to be shut in one by one depending on the cost coefficients and the specified field load requirement.
- In effect, the program provides an explicit ranking of the wells since the higher the cost coefficient, the greater is the potential for thermal breakthrough between the injector/producer pair of wells.

4.3 Quadratic Programming

The quadratic programming formulation **(QPAL)** with its accompanying constraints are given by Equation **4.8.** The flowcharts, program codes, and data-entry programs can be found in Lovekin(1987).

Minimize

$$B = \sum_{i=1}^{N_1}\sum_{j=1}^{N_2} c_{ij} q_{ri} q_{pj} \tag{4.8}$$

Subject to

$$\begin{aligned}
q_{ri} &\leq q_{rimax}, & i = 1,\ N_1 \\
q_{pj} &\leq q_{pjmax}, & j = 1,\ N_2 \\
\sum q_{ri} &= Q_{rtot} & \\
\sum q_{pj} &= Q_{ptot} & \\
q_{ri} &\geq 0, & i = 1,\ N_1 \\
q_{pj} &\geq 0, & j = 1,\ N_2
\end{aligned}$$

As Equation **4.8** shows, in quadratic programming, the injection and production rates are treated simultaneously as decision variables and, therefore, are included in the objective function B as a product. The problem is then solved by a quadratic programming solver **(QPSOL)** which treat the arc costs as elements of a Hessian matrix of second order derivatives of the objective. For a detailed discussion of the theory behind the solver, the reader is referred to the Lovekin (1987).

4.4 Case Results and Discussion

The input data for the optimization strategy using linear programming and quadratic programming are shown in Table 4.1. The objective of this exercise is to determine and compare how the two algorithms would allocate injection rates between the two injection wells and production rates among the different Palinpinon-I production wells. Only the results of the radioactive tracer tests are used because the parameters available from the sodium fluorescein tests are not sufficient. To illustrate, only the breakthrough times of the dye were quantified during the Palinpinon fluorescein tracer tests.

For the radioactive tracer tests, the parameters used as weighting factors for the arc cost are the mean transit time, t_m and the fractional recovery f. Due to the inherent limitation of tracer tests, some of the tracer parameters may not be known or can not be obtained for some injector/producer pairs. As an example, there may be no tracer return on some monitored wells or some producing wells had not been monitored due to operational constraints. In the first case of no positive return, parameters which are directly proportional to thermal breakthrough, such as C_p or f, are entered as zeros. This calculates a zero arc cost which signifies the absence of thermal breakthrough along this arc. To prevent division by zero for parameters such as t_i or t, which are inversely related to thermal breakthrough, arbitrarily large numbers had been entered to produce negligibly small arc costs. For the second case where tracer data are missing or lacking, the tracer parameters are entered in a similar fashion as the first. This is a drawback of the program, since it can not distinguish between no response and missing information This drawback can be overcome by implementing more comprehensive tracer tests.

For field geometry, the only weighting factor that has been included is the vertical distance, h, between the producing and injecting zones. Aerial horizontal distance, L, between wells has not been utilized as a weighting factor since the study of Lovekin (1987) has shown that the use of this parameter alone $(1/L^2)$ produced results which are totally different from those which employed tracer test parameters. Given the fractured nature of the Palinpinon field where the conduits of fluid flow are geological faults or structures, the same results had been verified. Appendix A lists a table of the production and injection zones of the Palinpinon wells.

Table **4.1:** Input data **for** optimization strategy.

	Monitored Wells	Mean Transit Time, days t_m	Fractional Recovery f	Vertical * Distance, m h	Production Rate, kg/s q_{pt}	Horizontal** Distance, m L
OK-12RD	OK-7	14.6	0.0128	4 11	87.0	960
Tracer Test	OK-10D	13.8	0.0135	-221	50.0	1150
	PN-15D	7.3	0.0035	-393	68.0	780
	PN-17D	3.9	0.1306	9	46.0	400
	PN-21D	4.0	0.0010	-781	39.0	940
	PN-26	5.0	0.0010	-46	95.0	860
	PN-28	6.0	0.0058	4 %	36.0	795
PN-9RD	OK-7	5.4	0.2 170	-238	47.0	960
Tracer Test	PN-16D	16.0	0.0010	-684	37.6	1290
	PN-18D	17.2	0.0163	586	33.0	1280
	PN-19D	16.0	0.0010	-1308	68.0	900
	PN-23	15.8	0.0040	-1489	58.9	1480
	PN-26	13.0	0.0046	811	3.0	815
	PN-28	14.0	0.0044	1161	7.0	850
	PN-29D	15.4	0.0790	-187	51.8	990
	PN-30D	15.7	0.0080	-1582	59.3	1390
	PN-31D	16.0	0.0164	-243	17.3	835

*Vertical distance is producing depth minus injecing depth.
**Aerial distance from major producing to major injecting zone.

Since not all the monitored production wells and injection wells were producing or injecting at maximum capacities during the tracer tests, the production and injection rates during the tracer tests, q_{pt} and q_{rt} were included as weighting factors. Appendices B and C include in the input the maximum operating production and injection flowrates of the Palinpinon wells during the tracer testing.

The tracer parameters for the OK-12RD tracer test were obtained from the report of the Philippine Atomic Energy Commission (PAEC) which conducted the two tracer tests and are reproduced in Table 3.1. However, for the PN-9RD tracer test, the values used for t_m and f were a combination of the PAEC and PNOC values.

4.4.1 Sensitivity to Weighting Factors

Before the runs on allocation, sensitivity in the arc costs were conducted to probe into the effects of the different weighting factors on the two algorithms. Tables 4.2 and 4.3 show the results of using the weighting factors either singly, or in combinations.

From Tables 4.2 and 4.3, it will be noted that:

All the runs produced the same ranking and allocation for the two injectors. PN-9RD was seen to be more detrimental as suggested by its higher cost coefficient, and subsequently, injection into it was reduced.

The only exception, which viewed OK-12RD as more damaging is Run 5, which uses the elevation parameter alone (e^{sh}). This run also produced totally different ranking of producing wells, although three of the curtailed wells (PN-26, PN-28, and PN-18D) appear to be in common with the rest of the results. (See also Table 4.4.)

The use of each weighting factor alone (Runs 1-4) gives results which are slightly different from each other. A list of the weighting factors acting individually and the corresponding "priority" wells which have been curtailed but not necessarily

Table 4.2: A. Sensitivity **to** different weighting factors.

		L	P	A	L		Q	P	A L
Weighting Factor	Injectors	Amount Injected,kg/s	Cost Coefficients	Curtailed Producers	Amount Curtailed,kg/s	Cost Coefficients	Amount Injected,kg/s	Curtailed Producers	Amount Curtailed,kg/s
11. 1/tp	OK-12RD	165	00019.5400	OK-7	Total	0045.23	165	OK-7	T d
	PN-9RD	95	00033.0500	PN-17D	Tarl	0043.26	95	PN-17D	Toul
				PN-21D	Total	0042.20		PN-21D	Total
				PN-26	Tarl	0039.79		PN-26	Tarl
				PN-28	Total	0035.42		PN-28	Toul
				PN-15D	17/12	0023.56		PN-15D	17/72
2. f	OK-12RD	165	00000.3570	OK-7	Total	0023.71	165	OK-7	Toul
	PN-9RD	95	00001.7450	PN-17D	Total	0021.55	95	PN-17D	Toul
				PN-29D	Total	0006.65		PN-29D	Toul
				OK-10D	Total	0002.23		OK-10D	Toul
				PN-18D	Total	0001.55		PN-18D	T d
				PN-28	41/59	OO01.38		PN-28	41/59
13. e^sh	OK-12RD	159	00689.7000	PN-14	Tarl	0428.00	165	PN-14	T d
	PN-9RD	101	00392.7000	PN-28	Total	0419.00	95	PN-28	Total
				PN-26	Tarl	0379.00		PN-26	T d
				PN-19D	Toul	03S9.00		PN-19D	Total
				PN-18D	Total	0342.00		PN-18D	Toul
				OK-9D	40/45	0230.00		OK-9D	4/45
4. 1/qpt	OK-12RD	165	00004.4479	PN-26	Total	0033.40	165	PN-26	Toul
	PN-9RD	95	00010.1931	PN-28	Total	0016.92	95	PN-28	Toul
				PN-29D	Total	001453		PN-29D	Toul
				PN-17D	Toul	0008.72		PN-17D	Toul
				PN-31D	Total	0005.66		PN-31D	Toul
				PN-21D	26/51	0004.33		PN-21D	26/51
IS. 1/tp, e^sh	OK-12RD	165	00000.0137	PN-26	Total	0046.78	165	PN-26	Total
	PN-9RD	95	00000.0702	PN-17D	Total	0043.08	95	PN-17D	Total
				PN-28	Total	0042.03		PN-28	Toul
				OK-7	Total	0035.44		OK-7	Toul
				PN-21D	Total	0019.34		PN-21D	Toul
				PN-15D	17/72	0015.52		PN-15D	55/72
6. 1/tp, f	OK-12RD	165	000.0348	OK-7	Toul	009.640	165	OK-7	Toul
	PN-9RD	95	000.1276	PN-17D	Toul	005.530	95	PN-17D	Toul
				PN-29D	Tarl	000.410		PN-29D	Total
				PN-28	Tarl	000.190		PN-28	T d
				OK-10D	Total	000.160		OK-10D	Toul
				PN-18D	46/64	000.098		PN-18D	18/64
17. f, e^sh	OK-12RD	165	000.3640	OK-7	Total	023.310	165	OK-7	Total
	PN-9RD	95	001.4110	PN-17D	Total	021.740	95	PN-17D	Toul
				PN-29D	Total	005.520		PN-29D	Toul
				PN-18D	Total	002780		PN-18D	Toul
				PN-28	Toul	001.920		PN-28	T d
				OK-10D	3462	001.790		OK-10D	1862

Table 4.3: **B.** Sensitivity to different weighting factors.

		L	P	A	L		Q	P	A L
Weighting Factor	**Injectors**	**Amount Injected,kg/s**	**Cost Coefficients**	**Curtailed Producers**	**Amount Curtailed,kg/s**	**Cost Coefficients**	**Amount Injected,kg/s**	**Curtailed Producers**	**Amount Curtailed,kg/s**
8. 1/tp, f, e^sh	OK-12RD	165	000.0375	OK-7	Total	007.920	165	OK-7	Total
	PN-9RD	95	000.0972	PN-17D	TOU	005.580	95	PN-17D	Total
				PN-29D	Total	000.340		PN-29D	Total
				PN-28	TOU	000.210		PN-28	Total
				PN-18D	TOU	000.180		PN-18D	Total
				OK-10D	34152	000.130		OK-10D	18152
9. 1/tp, 1/qpt	OK-12RD	165	000.2771	PN-26	Total	002.610	165	PN-26	Total
	PN-9RD	95	000.6836	PN-28	Total	001.790	95	PN-28	Total
				PN-21D	Total	001.060		PN-21D	Total
				PN-17D	Total	000.970		PN-17D	Total
				OK-7	Total	000.850		OK-7	Total
				PN-31D	48/65	000.340		PN-31D	48/65
10. f, 1/qpt	OK-12RD	165	000.0176	OK-7	Total	000.590	165	OK-7	Total
	PN-9RD	95	000.0620	PN-17D	Total	000.470	95	PN-17D	Total
				PN-26	TOU	000.145		PN-26	Total
				PN-29D	Total	000.128		PN-29D	Total
				PN-28	Total	000.081		PN-28	Total
				PN-18D	3/64	000.047		PN-18D	3/64
11. f, 1/tp, 1/qpt	OK-12RD	165	000.0015	OK-7	Total	000.204	165	OK-7	Total
	PN-9RD	95	000.0040	PN-17D	Total	000.120	95	PN-17D	Total
				PN-26	Total	000.010		PN-26	Total
				PN-28	Total	000.009		PN-28	Total
				PN-29D	Total	000.008		PN-29D	Total
				OK-10D	3/52	000.003		OK-1OD	3/52
12. f, 1/qpt, e^sh	OK-12RD	165	0.0137	OK-7	TOU	0.4800	165	OK-7	Total
	PN-9RD	95	0.0702	PN-17D	Total	0.4700	95	PN-17D	Total
				PN-26	Total	0.3300		PN-26	Total
				PN-28	Total	0.1900		PN-28	Total
				PN-29D	Total	0.1100		PN-29D	Total
				PN-18D	3/64	0.0840		PN-18D	3/64
13. f, 1/qpt, 1/tp e^sh	OK-12RD	165	0.0012	OK-7	Total	0.1680	165	OK-7	Total
	PN-9RD	95	0.0044	PN-17D	Total	0.1210	95	PN-17D	Total
				PN-26	Total	0.0230		PN-26	Total
				PN-28	Total	0.0170		PN-28	TOU
				PN-29D	Total	0.0066		PN-29D	TOU
				PN-18D	3/64	0.0053		PN-18D	3/64
14. f, 1/qpt, 1/tp 1/qrt, e^sh	OK-12RD	165	0.0010	OK-7	TOU	0.0992	165	OK-7	TOU
	PN-9RD	95	0.0060	PN-17D	Tarl	0.0468	95	PN-17D	Total
				PN-26	Total	0.0139		PN-26	Tarl
				PN-28	Total	0.08%		PN-28	Total
				PN-29D	Total	0.0039		PN-29D	Total
				PN-18D	3/64	0.0032		PN-18D	3/64

Table 4.4: Ranking of wells using individual weighting factors.

All weighting factors	f	tp	qpt	h
OK-7	OK-7	OK-7		
PN-17D	PN-17D	PN-17D	PN-17D	
PN-26		PN-26	PN-26	PN-26
PN-28	PN-28	PN-28	PN-28	PN-28
PN-29D	PN-29D		PN-29D	
PN-18D	PN-18D			PN-18D
	OK-1OD			
		PN-21D	PN-21D	
		PN-15D		
			PN-31D	
				PN-14
				PN-19D

according to rank as shown in Tables 4.2 and 4.3 is given by Table 4.4. The first column from Table 4.4 represents the ranking when all the weighting factors are combined in a single run. It can be noted that the use of f alone (Run 2) comes closest to the result when all weighting factors are used (Run 13). The only difference between the two, aside from ranking of the wells, is the presence of PN-26 in Run 13 (all factors) which have supplanted OK-1OD in Run 2 (only f).

Both the use of t_p and q_{pt} individually produced four of the six wells obtained in the final run. However, since q_{pt} is more of a well-specific weighting factor, its use is expected to produce results which are different from those of tracer test parameters.

As the weighting factors are combined, the results approach that of Run 13. The interplay of the other factor(s) produces the final outcome. The presence of a well in two or more factors used singly would usually increase the priority of that well in a run that combines the concerned factors.

To illustrate, the only difference between Run 11 (f, q_{pt}, t_p) and Run 12 (f, q_{pt}, h) is the presence of OK-1OD for Run 11 which had been replaced by PN-18D for Run 12. Whereas OK-1OD has a higher priority than PN-18D in Run 2 using f alone, the inclusion of h as another factor in Run 12 having PN-18D and not OK-10D, causes the switch.

The last three runs, (Runs 12-14) using a minimum of three weighting factors, (f, q_{pt}, and h), all reproduced the same wells that had to be curtailed (OK-7, PN-17D, PN-26, PN-28, PN-29D, and PN-18D) in exactly the same order. Using the two weighting factors, f and q_{pt}, (Run 10) also gave the same wells although PN-29D was interchanged with PN-28 in order. This is due to the fact that PN-29D appears both in Runs 2 and 4 using f and q_{pt} individually, whereas PN-28 appears in Runs 1-4 utilizing the four factors singly. Hence, with runs employing more than the f and q_{pt} factors together (*e.g.* Runs 11-14), PN-28 is given a higher priority than PN-29D.

Figure **4.2** illustrates the flow of results as the weighting factors are increased one by one. Starting with f alone as the weighting factor (Run 2), the ranking is OK-7, PN-17D, PN-29D, OK-10D, PN-18D, and PN-28. With the addition of t_p, the same wells are curtailed, but the ranking is now OK-7, PN-17D, PN-29D, PN-28, OK-10D, PN-18D. This seemingly implies that the factor f has more weight than the factor t_p. It also means that with both f and t_p (Run 6), PN-28 is accorded a higher priority to OK-1OD and PN-18D. This can be explained by an examination of Run 1 using t_p alone showing that PN-28 has been curtailed, whereas OK-1OD and PN-18D have not been. Adding q_{pt} to the two weighting factors (Run 11) has the effect of inserting PN-26 and deleting PN-18D, so that the ranking changes to OK-7, PN-17D, PN-26, PN-28, PN-29D, and OK-10D. A look at Run **4,** which uses q_{pt} alone, indicates that PN-26 has been judged the most susceptible to breakthrough (that is, it ranks first) followed by PN-28. Hence, when q_{pt} is added to the combination of f and t_p, the two precede PN-29D and strike out PN-18D, which does not appear in either Run 1 (f) or Run

WEIGHTING FACTORS			
f	f, 1/tp	f, 1/tp, 1/qpt	f, 1/tp, 1/qpt, e^sh
OK-7	OK-7	OK-7	OK-7
PN-17D	PN-17D	PN-17D	PN-17D
	PN-29D	PN-26	PN-26
OK-10D	PN-28	PN-28	PN-28
PN-18D	OK-10D	PN-29D	PN-29D
PN-28	PN-18D	OK-10D	PN-18D

Figure **4.2:** Ranking of wells with increase in weighting factors.

4 (q_p). Finally, when h is added to the three factors (f, t_p, q_{pt}), it is surprising to see that **PN-18D** is reinstated in place of **OK-10D.** The same reasoning to the third item above applies in this situation. Since **PN-18D** ranks high in both f (Run **2)** and h (Run **3),** whereas **OK-1OD is** prioritized only **in** f (Run **2),** the the final ranking of **OK-7, PN-17D, PN-26, PN-28, PN-29D,** and **PN-18D,** excludes **OK-10D.**

In summary, due to the results of the two tracer tests, the use of the tracer return parameters acting individually **as** weighting factors tended to give results which are slightly different from each other. **As** weighting factors were combined, the results became similar and gravitated to the final run using all factors. The appearance of a well in more than one single factor resulted in a higher priority for the well when these factors where utilized simultaneously. Unlike Lovekin's **(1987)** study, the use of the elevation parameter alone (e^{sh}) showed results which are in greater disparity with the rest.

4.4.2 Allocation of Production Rates

Tables **4.5** and **4.6** show the results of using the two algorithms to allocate production and injection rates among the different Palinpinon wells. The scenario assumes only two injection wells, **OK-12RD** and **PN-9RD,** which have maximum injection capacities of **165** kg/s and **101** kg/s, respectively. The required fieldwide production rate is **930 kg/s** which will be provided by the **21** production wells which have a combined capacity of **1294** kg/s. Out of this produced fluid, 260 kg/s will be reinjected back into the two injection wells. Appendix B and Appendix C show sample outputs from the two algorithms but for brevity Tables **4.5** and **4.6** only list the producers which have been curtailed, totally or partially.

Aside from the first scenario, Tables **4.5** and **4.6** also show what happens **as** the required field rate Q_{ptotal} is reduced from **930** kg/s to **450** kg/s. From Appendices B and C, it can be seen that:

- Because PN-9RD is perceived as the more damaging of the two injectors, (its coefficient for LPAL is higher than that of OK-12RD), injection into it is reduced from a maximum of **101** kg/s to **95** kg/s. OK-12RD, which is less damaging, has to inject at full capacity because of the specified fieldwide injection rate requirement.
- LPAL provides an explicit ranking of the wells by virtue of their cost coefficients which, however, is absent in QPAL. In spite of this, it is worthwhile to reiterate Lovekin's study **(1987)** that QPAL assesses the quality of each solution as being "optimal", or "weak local minimum" when cost coefficients are equal for more than one well.
- Convergence in LPAL is usually achieved in three iterations. Injection rates are solved for the first and third iterations, while production rates are determined in the second iteration. As stated before, the first iteration uses maximum production rates (q_{pjmax}) as weighting factors to solve for injection rates due to the absence of previously solved production rates.

Table 4.5: A. Allocation of production rates to Palinpinon **Wells.**

		L	P	A	L		Q	P A	L
Qptotal kg/s	Injectors	Amount Injected,kg/s	Cost Coefficients	Curtailed Producers	Amount Curtailed,kg/s	Cost Coefficients	Amount Injected,kg/s	Curtailed Producers	Amount Curtailed,kg/s
1. 930	OK-12RD	165	0.00100	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	0.00591	PN-17D	Total	0.046800	PN-9RD	PN-17D	TOU
				PN-26	TOU	0.013900		PN-26	Total
				PN-28	Total	0.009600		PN-28	TOU
				PN-29D	TOU	0.003900		PN-29D	TOU
				PN-18D	3/64	0.003200		PN-18D	3/64
2 900	OK-12RD	165	0.00100	OK-7	TOU	0.099200	OK-12RD	OK-7	TOU
	PN-9RD	95	0.00366	PN-17D	TOU	0.046800	PN-9RD	PN-17D	Total
				PN-26	Total	0.013900		PN-26	Total
				PN-28	Toul	0.009600		PN-28	Total
				PN-29D	TOU	0.003900		PN-29D	Total
				PN-18D	33/64	0.003200		PN-18D	33/64
3. 850	OK-12RD	165	0.00100	OK-7	TOU	0.099200	165	OK-7	Total
	PN-9RD	95	0.00177	PN-17D	TOU	0.046800	95	PN-17D	TOU
				PN-26	TOU	0.013900		PN-26	TOU
				PN-28	TOU	0.009600		PN-28	Total
				PN-29D	TOU	0.003900		PN-29D	TOU
				PN-18D	Toul	0.003200		PN-18D	TOU
				OK-10D	19/52	0.001000		OK-10D	19/52
4. 800	OK-12RD	165	0.00100	OK-7	TOU	0.099200	165	OK-7	Total
	PN-9RD	95	0.00354	PN-17D	Toul	0.046800	95	PN-17D	TOU
				PN-26	Total	0.013900		PN-26	Total
				PN-28	TOU	0.009600		PN-28	TOU
				PN-29D	Total	0.003900		PN-29D	TOU
				PN-18D	Total	0.003200		PN-18D	Total
				OK-10D	Total	0.001000		OK-10D	Total
				PN-31D	17/65	0.000640	165	PN-31D	17/65
5. 750	OK-12RD	165	0.00100	OK-7	Toul	0.099200	95	OK-7	Total
	PN-9RD	95	0.00116	PN-17D	Total	0.046800		PN-17D	Total
				PN-26	TOU	0.013900		PN-26	Total
				PN-28	Toul	0.009600		PN-28	Total
				PN-29D	TOU	0.003900		PN-29D	TOU
				PN-18D	TOU	0.003200		PN-18D	Total
				OK-10D	Total	0.001000		OK-10D	TOU
				PN-31D	Total	0.000640		PN-31D	Total
				PN-15D	2/12	0.000300		PN-15D	2/12
6. 700	OK-12RD	165	0.00100	OK-7	TOU	0.099200	165	OK-7	TOU
	PN-9RD	95	0.00403	PN-17D	TOU	0.046800	95	PN-17D	Total
				PN-26	Total	0.013900		PN-26	TOU
				PN-28	Total	0.009600		PN-28	Total
				PN-29D	TOU	0.003900		PN-29D	Total
				PN-18D	Total	0.003200		PN-18D	TOU
				OK-10D	TOU	0.001000		OK-10D	TOU
				PN-31D	Total	0.000640		PN-31D	Total
				PN-15D	52/72	0.000300		PN-15D	52/72
7. 650	OK-12RD	165	0.00100	OK-7	TOU	0.099200	165	OK-7	TOU
	PN-9RD	95	0.20320	PN-17D	Total	0.046800	95	PN-17D	Total
				PN-26	Total	0.013900		PN-26	Tarl
				PN-28	TOU	0.009600		PN-28	Total
				PN-29D	Total	0.003900		PN-29D	Total
				PN-18D	Total	0.003200		PN-18D	Total
				OK-10D	Total	0.001000		OK-10D	Total
				PN-31D	TOU	0.000640		PN-31D	TOU
				PN-15D	Tarl	0.000300		PN-15D	Total
				PN-30D	30/71	0.000095		PN-30D	30/71

Table **4.6:** B. **Allocation of** production rates to Palinpinon Wells.

	Qtotal kg/s	Injectors	L Amount Injected,kg/s	P Cost Coefficients	A Curtailed Producers	L Amount Curtailed,kg/s	Cost Coefficients	Q Amount Injected,kg/s	P Curtailed Producers	A L Amount Curtailed,kg/s
8.	600	OK-12RD	165	0.00100	OK-7	Total	0.099200	165	OK-7	Total
		PN-9RD	95	0.12100	PN-17D	Tarl	0.046800	95	PN-17D	Total
					PN-26	Total	0.013900		PN-26	Total
					PN-28	Total	0.009600		PN-28	Total
					PN-29D	Total	0.003900		PN-29D	Total
					PN-18D	Total	0.003200		PN-18D	Total
					OK-10D	Total	0.001000		OK-1OD	Total
					PN-31D	Total	0.000640		PN-31D	Total
					PN-15D	Total	0.000300		PN-15D	Total
					PN-30D	Total	0.000095		PN-30D	Total
					PN-16D	9/46	0.000047		PN-16D	9/46
9.	550	OK-12RD	165	0.00100	OK-7	Total	0.099200	165	OK-7	TOU
		PN-9RD	95	0.07630	PN-17D	Total	0.046800	95	PN-17D	Total
					PN-26	Total	0.013900		PN-26	Total
					PN-28	Total	0.009600		PN-28	Total
					PN-29D	Total	0.003900		PN-29D	Total
					PN-18D	Total	0.003200		PN-18D	Total
					OK-10D	Total	0.001000		OK-10D	Total
					PN-31D	Tarl	0.000640		PN-31D	Total
					PN-15D	Total	0.000300		PN-15D	TOU
					PN-30D	Total	0.000095		PN-30D	Total
					PN-16D	Total	0.000047		PN-16D	Total
					PN-23D	13/73	0.000055		PN-23D	13/73
10.	500	OK-12RD	165	0.00100	OK-7	TOU	0.099200	165	OK-7	TOUL
		PN-9RD	95	0.02660	PN-17D	Total	0.046800	95		Total
					PN-26	Tarl	0.013900		PN-26	Total
					PN-28	Total	0.009600		PN-28	Total
					PN-29D	Total	0.003900		PN-29D	Total
					PN-18D	Total	0.003200		PN-18D	Total
					OK-10D	Total	0.001000		OK-10D	Total
					PN-31D	Tarl	0.000640		PN-31D	Total
					PN-15D	Total	0.000300		PN-15D	TOU
					PN-30D	Total	0.000095		PN-30D	Total
					PN-16D	Total	0.000047		PN-16D	Total
					PN-23D	63/73	0.000055		PN-23D	63/73
11.	450	OK-12RD	165	0.00100	OK-7	Total	0.099200	165	OK-7	Total
		PN-9RD	95	0.00650	PN-17D	Tarl	0.046800	95	PN-17D	Total
					PN-26	Total	0.013900		PN-26	Total
					PN-28	Total	0.009600		PN-28	Total
					PN-29D	Total	0.003900		PN-29D	TOU
					PN-18D	Total	0.003200		PN-18D	Total
					OK-10D	Total	0.001000		OK-10D	Total
					PN-31D	Total	0.000640		PN-31D	Total
					PN-15D	Total	0.000300		PN-15D	TOU
					PN-30D	Tarl	0.000095		PN-30D	Total
					PN-16D	Total	0.000047		PN-16D	Total
					PN-23D	Total	0.000055		PN-23D	Total
					PN-19D	40/66	0.000014		PN-19D	40/66

The arc costs are solved, then summed up to find the cost coefficients for the two injectors. After LPAL optimization, the injection rates are assigned. For the second iteration, the injection rates determined from the first are included as weighting factors to obtain the arc costs, which are then summed to find the cost coefficients of the producing wells. Optimization follows and production rates are calculated. The third iteration then uses these production rates as weighting factors and repeats the same procedure all over again to obtain the final injection rates. Since these rates are similar to those obtained from the first iteration, execution is halted; otherwise, the cycle is resumed until convergence is achieved. When the initial feasible solution identified in Phase I is also the optimal solution, the fieldwide breakthrough indices are identical for Phases I and II.

- Cycling in LPAL has not been observed during the numerous runs executed. Nevertheless, to prevent this from occurring, the input asks for the maximum allowable number of iterations.
- Production wells not shown in Tables 4.5 and 4.6 produce at maximum capacity while production wells deemed to suffer thermal breakthrough are ranked and shut-in accordingly. On the basis of the input data, the program ranks OK-7, PN-17D, PN-26, PN-28, PN-29D, and PN-18D as wells most vulnerable and, consequently, curtails them completely. As the required fieldwide production rate is reduced, Tables 4.5 and 4.6 show varying injection cost coefficients and throttling of the production wells one by one. However, since ranking and allocation of the injectors are the same for all cases, the cost coefficients for the producers remain the same.
- It can be concluded that QPAL and LPAL allocate the same rates to injection and producing wells.

Section 5

Use of Chloride Data

The preceding section has shown that the algorithms using linear and quadratic programming in conjunction with tracer data, field geometry and field operating conditions can be used to allocatk production and injection rates among the different Palinpinon wells. With tracer tests, especially radioactive tracer tests, it is possible to quantify the rate and extent of interaction between a producing and reinjecting well. Studies (LANL, 1987) have shown that by periodically injecting chemically reactive tracers for the appropriate temperature range and determining the extent of each reaction for each tracer in the production well, the movement of thermal fronts in a reservoir can be tracked with time. However, economic and operational constraints prohibit injecting tracers into each reinjection well and monitoring all the production wells. Therefore, attention was turned into finding other parameters that can be used in place of tracer data as input to the optimization routine. This parameter should be an arc-specific weighting factor manifesting a relationship between the injector and producer. Preferably, it should be sensitive to changes in the utilization of either well and at best, is independent of other injector and producer operating conditions.

One such parameter that has been inferred to show relationship between the injecting sector and the producing sector is the concentration of the chloride in the produced fluid. Figure 3.3 of Chapter 3 shows that reservoir chloride of producing wells increased soon after commissioning of the power plant Palinpinon-I. This general trend continued as illustrated by Figure 5.1 and has been used to demonstrate the extent of reinjection returns to the producing wells. Apprehensively, a producer that has sustained large injection returns as evidenced by steep increases in its production chloride is expected to encounter premature thermal breakthrough. In the Palinpinon-I, almost all production wells discharge reinjection fluids and the most affected wells are PN-29D, PN-26, PN-28, OK-7, PN-19D, and PN-23D (PNOC-EDC, 1990). Similarly affected, although to a lesser degree, are wells PN-18D, PN-31D, PN-15D, and PN-30D. Figure 5.2 shows decline in quartz equilibrium temperatures of production wells PN-26, OK-7, PN-19D, and PN-29D, due to large reinjection returns. The Palinpinon field experience has amply demonstrated the direct dependence between injected fluid returns and production chloride. The plots of the individual chloride measurements with time are given in Appendix D and those of injection flowrates in Appendix E.

It is, thus, the aim of this section to use the relationship of the chloride in place of tracer return data in the arc cost coefficients of the optimization schemes. The coefficient of correlation between chloride and flowrate has been obtained in four different ways as shown by Figure 5.3.

1. First, the correlation between the chloride value with time of a production well and the mass flowrate with time of an injection well was obtained (Figure 5.3a).
2. Second, the correlation between the chloride value with time of a production well and the *cumulative* mass flowrate with time of an injection well was calculated (Figure 5.3b).
3. Third, the correlation between the *deviation* of the chloride value from the best fit line and the flowrate of an injection well was computed (Figure 5.3c).

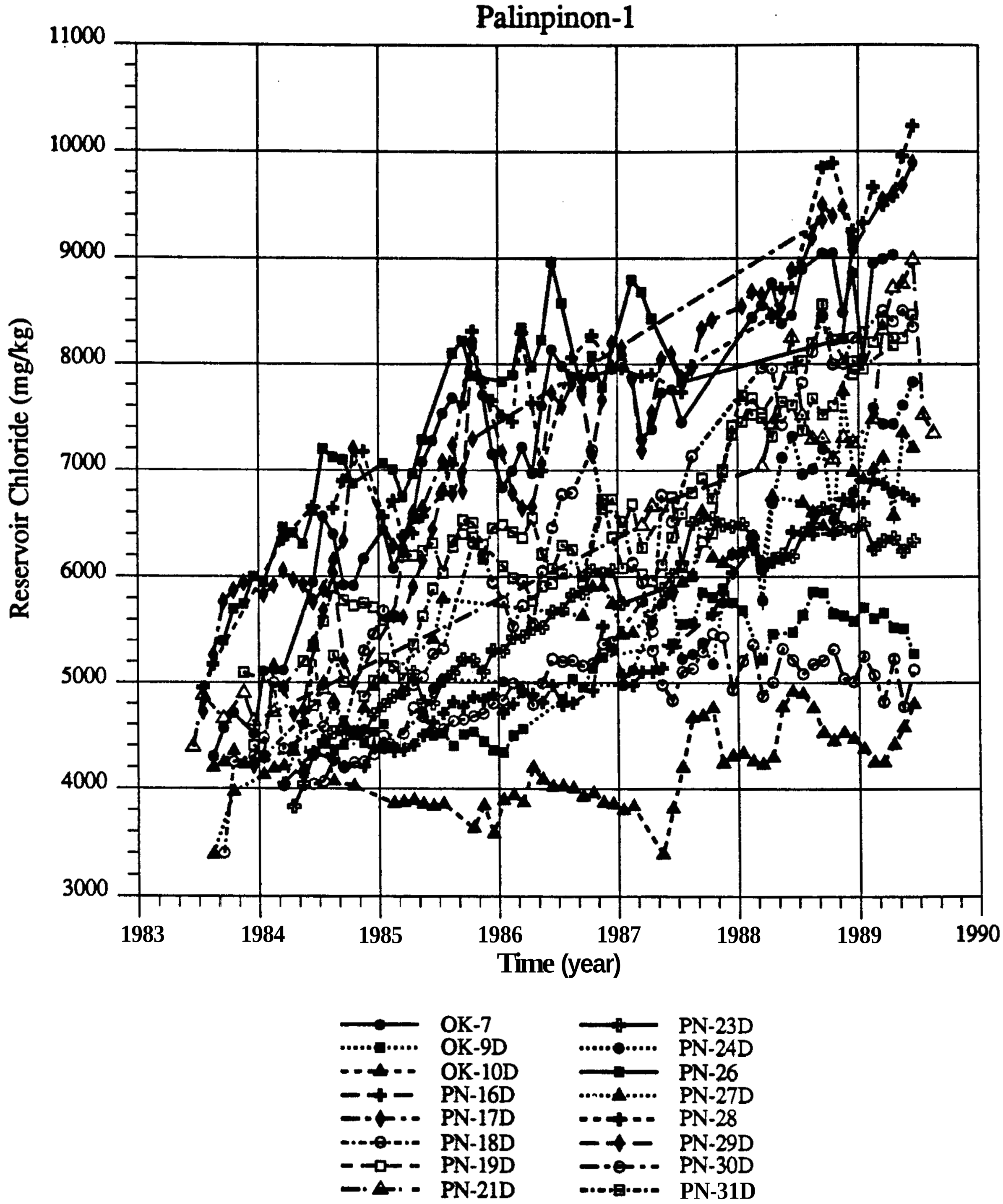


Figure 5.1: Palinpinon-I reservoir chloride measurements.

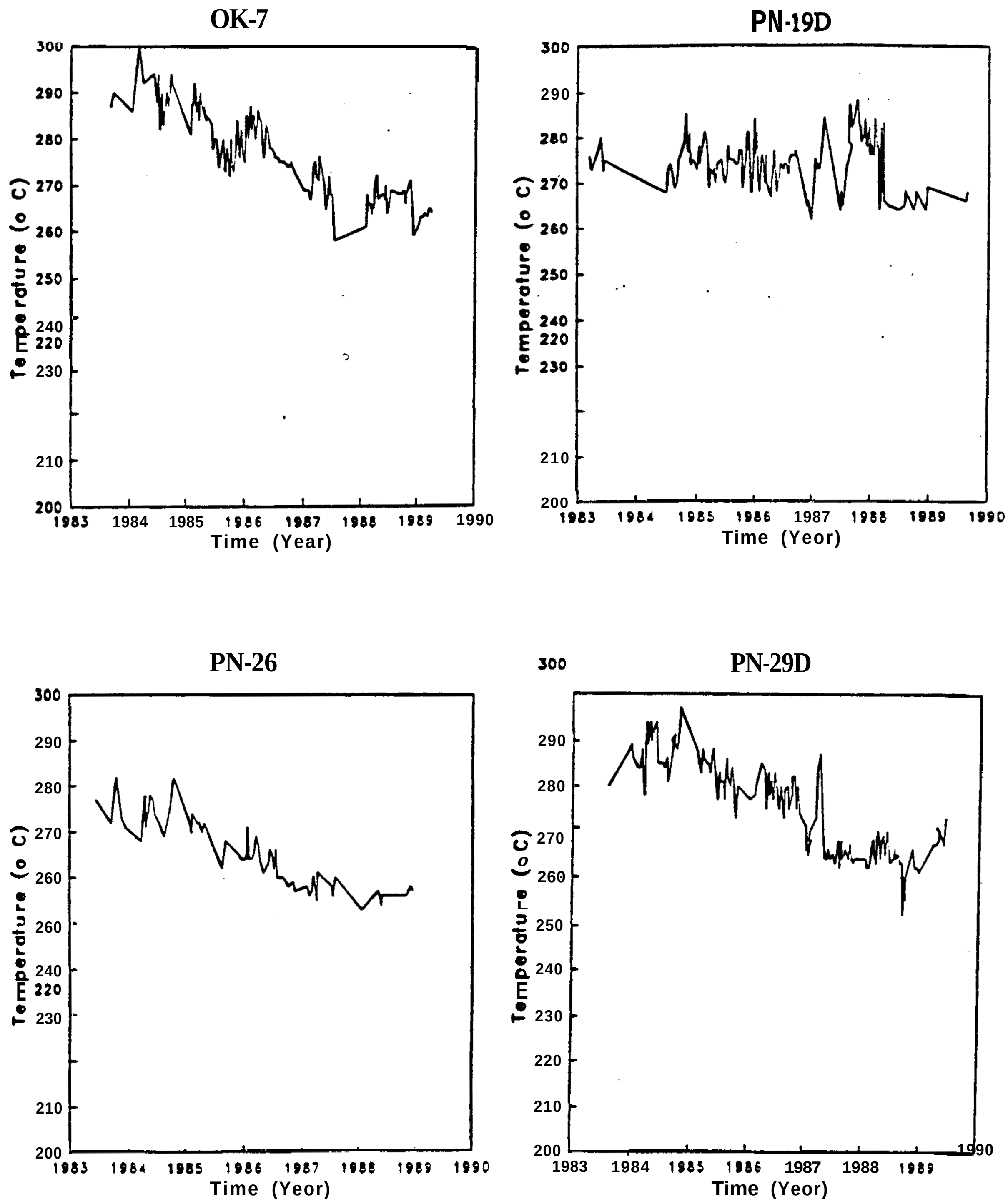


Figure **5.2:** Trend in quartz equilibrium temperatures. (after **PNOC-EDC,** 1990)

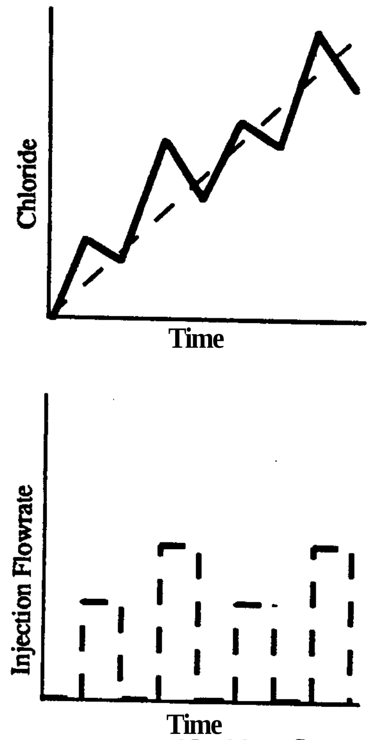


Figure 5.3a Chloride vs flowrate

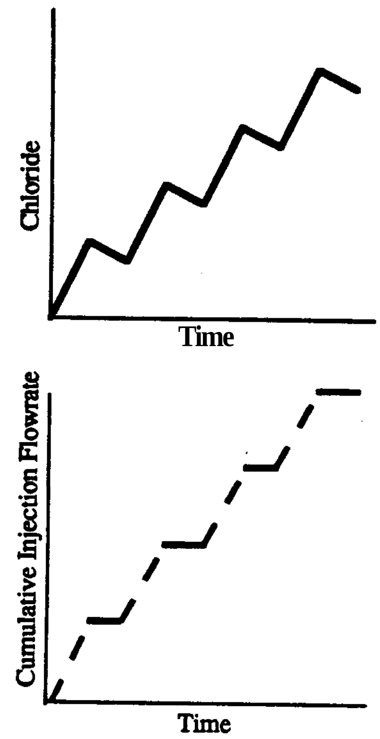


Figure 5.3b Chloride vs Cumulative flow

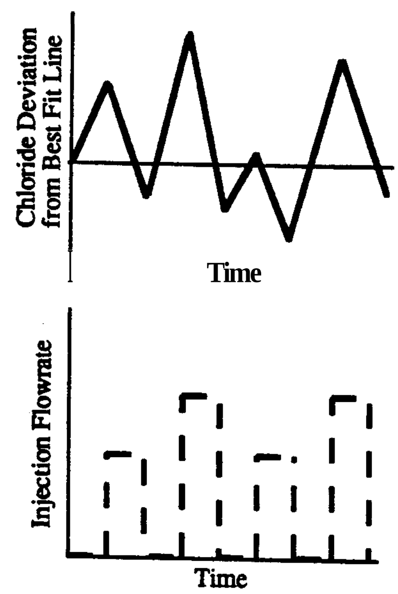


Figure 53c Chloride deviation vs Flowrate

Figure 5.3: Chloride vs flowrate correlation methods.

4. Lastly, the chloride value with time of a production well was expressed as a linear combination of the mass flowrates of the injection wells.

The two radioactive tracer tests (PN-9RD and OK-12RD) which show conclusively which reinjection well interacts with which production wells were used to test the applicability of the correlation method.

5.1 Chloride-Flowrate Correlation Method

By visual inspection of a figure similar to Figure 3.3, it has been observed that certain production wells react strongly to particular injection wells. If an injection well communicates intensely with a production well, then putting this injection well on line is usually followed by a substantial increase in the chloride measurements of the affected well. Once it is removed from service, there is an accompanying decrease in the chloride data of the producing well. It is assumed, then, that there is a linear relationship between the flowrate of an injection well, (q_{ri}), and the magnitude of the chloride value of a producing well, (cl_i). To obtain a measure of the strength of the linear relationship between these two variables, the coefficientof correlation r, independent of the respective scales of measurement, was calculated according to the formula:

$$r_{xy} = r_{yx} = \frac{\sum x_i y_i - n\bar{x}\bar{y}}{n s_x s_y} \tag{5.1}$$

where n is the number of data points, and:

$$\begin{aligned} \bar{x} &= \frac{\sum q_{ri}}{n} \\ \bar{y} &= \frac{\sum cl_i}{n} \\ s_x &= \sqrt{\frac{\sum q_{ri}^2}{n} - \bar{x}^2} \\ s_y &= \sqrt{\frac{\sum cl_i^2}{n} - \bar{y}^2} \end{aligned}$$

5.1.1 PN-9RD Tracer Test Application

Figure 5.4 shows the injection flowrates of injection well PN-9RD and the chloride values of production well OK-7. It can be recalled that the PN-9RD tracer test has shown immediate and large returns to OK-7 of the tracer injected into PN-9RD.

Figure 5.4 demonstrates the general trend of increasing chloride values of OK-7. The plot, however, is characterized by periods of steep ups and down in the chloride values. As an example, peaks occurred during the times June 1984, October 1985, and July 1986. On the other hand, PN-9RD was utilized only for two intervals of time: from April-July, 1984, and February-October, 1985. By looking at the graphs, one notes that the peak of PN-9RD use on July 1984 (40 kg/s) coincides exactly with the chloride peak of OK-7. Putting PN-9RD on service on April 1984 was followed immediately by large increases in OK-7 chloride values. However, if this increase in OK-7 chloride is attributed only to PN-9RD, the absence of the peaks and dips corresponding to the May-July use of PN-9RD, during which the monthly average injection flowrate of PN-9RD increased to 40 kg/s, down to 17 kg/s, and up again to 40 kg/s, would cast a doubt on the method. This can be explained by the fact that some precision on results had been sacrificed with the use of monthly averages. By plotting the raw data of OK-7 chloride with PN-9RD flowrate (Figure 5.5), the accompanying and expected effect on OK-7 for this interval is more evident. Nevertheless, the rest of the report shall continue to use monthly average chloride values for consistency with that of the injection flowrates. It is believed that in spite of this, the loss of finer details is not significant enough to alter the conclusions that have been reached.

For the second time interval (February-October, 1985) when PN-9RD was injecting in greater quantities (80 kg/s), there is also a corresponding increase and decrease in OK-7 chloride. It is interesting to observe that the start of the steep increase in OK-7 chloride (March 1985) coincides with a similar increase in injection into PN-9RD (from 5 to 71 kg/s). The peak, however, of OK-7 chloride

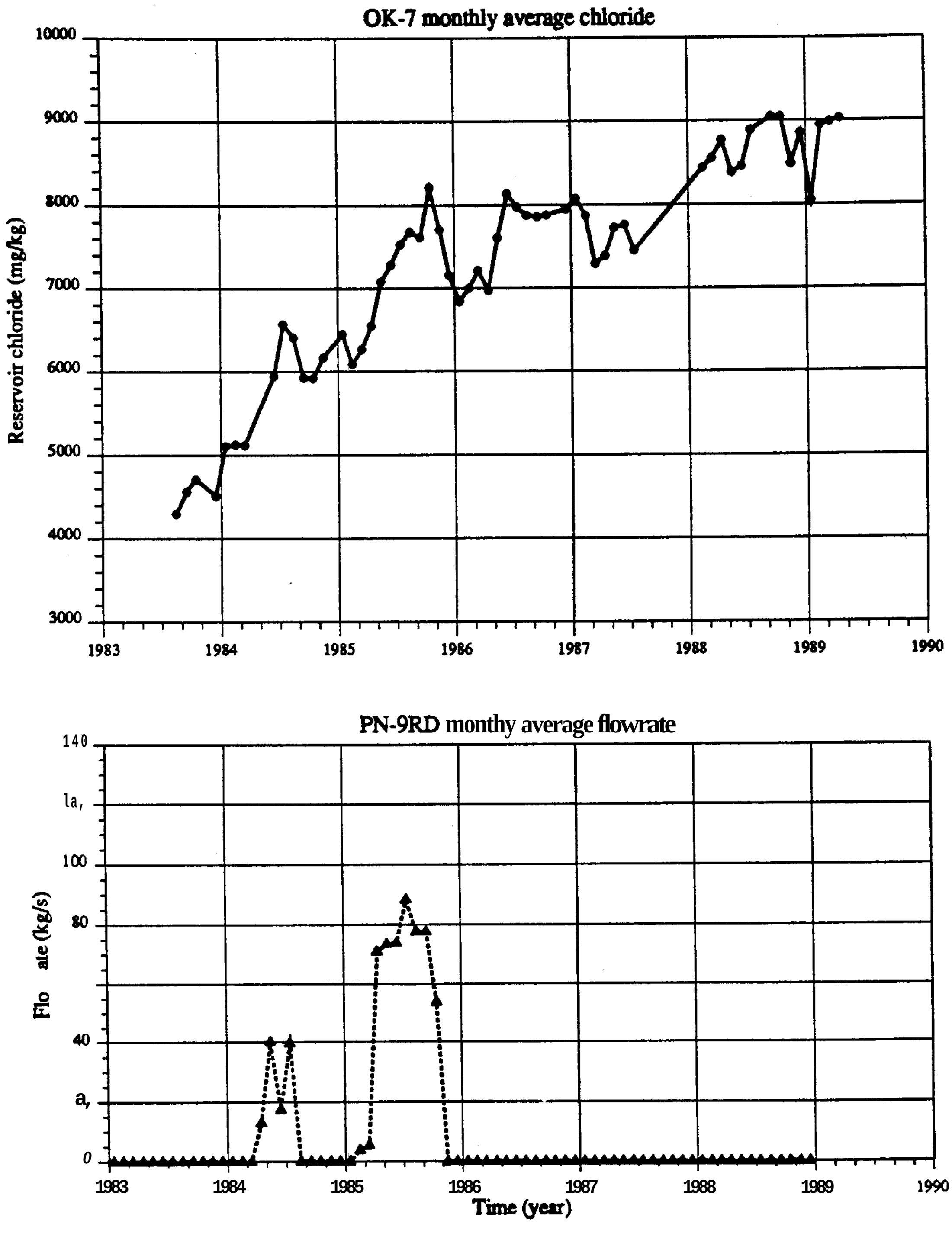


Figure 5.4: OK-7 monthly chloride and PN-9RD flowrate.

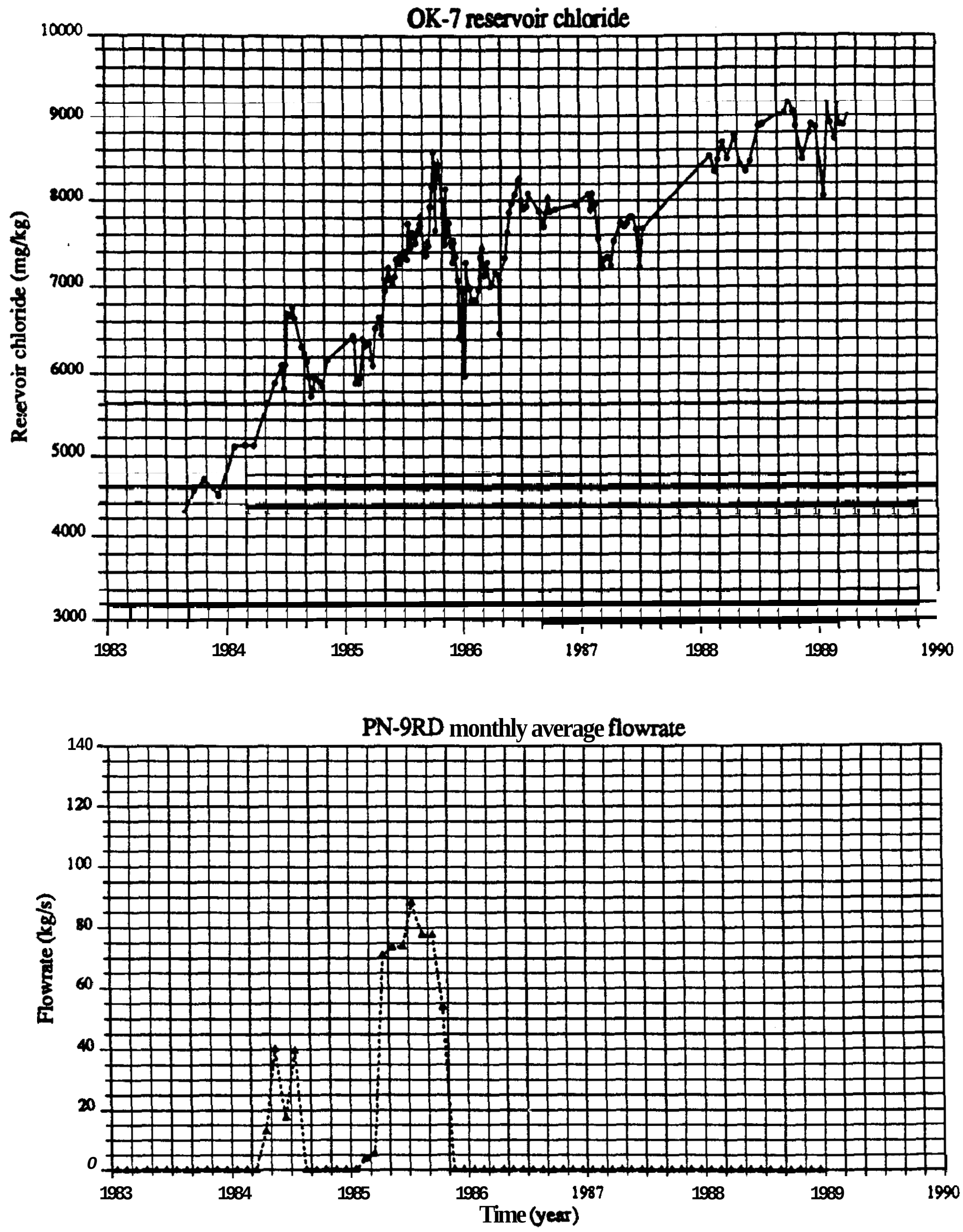


Figure 5.5: Using more OK-7 chloride measurements.

for this time interval (mid-October 1985) seems to lag that of PN-9RD's peak injection (August 1985). On a finer scale, Figure 5.5 does indeed show a local peak for OK-7 on August 26, 1985. When PN-9RD injection is sharply curtailed from 77kg/s in a month's time, there was also a subsequent steep decrease of OK-7 chloride. Since PN-9RD was taken out of service after October 1985, the question as to what injection well causes the further increase in OK-7 chloride shall be answered later.

The correlation between OK-7 chloride and PN-9RD flowrate was calculated using Equation 5.1. A sample output is given by Table 5.1 and the plot of OK-7/PN-9RD correlation with time is shown in Figure 5.6.

Figure 5.6 shows the OK-7/PN-9RD correlation curve consists of two humps, with the apexes matching the tips of either the chloride plot or flowrate plot. For these points, the coefficients of correlation are 0.90 and 0.80, respectively. Hence, the correlation plot shows positive coefficients when changes in chloride data are related in the same fashion to changes in the injection flowrates during the same time interval. It should be remembered that with time, the number of data points of both the chloride value and flowrates increases and, therefore, the coefficient of correlation that is calculated is cumulative with respect to time. With a step in time, the data set expands and covers the previous values. A quick glance at Figure 5.6 would show that the whole curve consistently lies above the zero correlation line. In other words, there is always a positive correlation between OK-7 and PN-9RD during the whole time interval considered. The decreasing coefficients of correlation with time after October 1985 is due to the fact that PN-9RD has already stopped injecting and OK-7 is still increasing in its chloride values. It would be interesting, then, to compare the coefficients before and after curtailing PN-9RD injection. In this case, since PN-9RD was on-line continuously for two periods of time, the average of the two was taken. As seen from Figure 5.6, the coefficients of correlation when PN-9RD stopped injecting on August 1984 and November 1985 are 0.69 and 0.71, respectively, giving an average of 0.70. On the other hand, the coefficients taken just before the well has stopped injecting are 0.90 and 0.80, or equivalently an average of

Table 5.1: OK-7/PN-9RD correlation.

TIME	R	R^2	sx	Sy
1983.7078	0.	0.	0.	0.
1983.7890	0.	0.	0.	0.
1983.9562	0.	0.	0.	0.
1984.0411	0.	0.	0.	0.
1984.1233	0.	0.	0.	0.
19842027	0.	0.	0.	0.
1984.4548	0.795745	0.633210	487.21267	5.73467
1984.5370	0.899839	0.809710	691.03703	12.92689
1984.6219	0.686513	0.471301	76253737	12.40918
1984.7078	0.620228	0.384682	75350367	11.94411
1984.7890	0569955	0.324848	741.61322	11.52454
1984.8740	0508174	0.258241	74527016	11.14420
1985.0411	0.437861	0.191723	765.66716	10.79776
1985.1233	0.427243	0.182537	754.60937	10.43213
1985.2027	0.422726	0.178697	752.30727	10.10660
1985.2877	0.467563	0218615	764.98983	18.54257
19853699	05886%	0.346563	813.96029	23.44158
1985.4548	0.670141	0.449088	866.12072	26.72367
19855370	0.735167	0.540470	925.18306	3055326
1985.6219	0.775284	0.601066	980.64734	3235392
1985.7078	0.801577	0.642525	1017.77733	33.709 19
1985.7890	0.793994	0.630427	1089.39101	33.52478
1985.8740	0.709547	0503456	1111.93705	33.20593
1985.9562	0.667435	0.445469	1105.47990	32.88004
1986.0411	0.642745	0.413121	1090.18314	3255069
1986.1233	0.615013	0.378240	1078.77530	32.22057
19862027	0.582209	0.338967	1073.18178	31.89170
19862877	0.560826	0.314526	1061.24394	31.56556
1986.3699	0519860	0.270254	1067.80336	31.24327
1986.4548	0.464339	0215610	1095.00912	30.92565
19865370	0.422322	0.178356	1110.56033	30.61328
1986.6219	0.388600	0.151010	1119 —38	30.30657
1986.7078	0359079	0.128938	1125.27644	30.00579
1986.7890	0332184	0.110346	1130.33462	29.71113
1986.9562	0.306413	0.093889	1136.16704	29.42267
1987.0411	0.280519	0.078691	1144.60234	29.14044
1987.1233	0.261057	0.068151	1145.38988	28.86442
19872027	0.252494	0.063753	1134.26480	28.59456
19872877	0.243152	0.059123	1124.62507	28.33078
1987.3699	0.229405	0.052627	1121.03414	28.072%
1987.4548	0216165	0.046727	1117.77560	27.82099
1987.5370	0207935	0.043237	1109.11947	2757475
1988.1233	0.186532	0.034794	1122.96411	27.33408
19882027	0.165568	0.027413	1138.53303	27.09886
1988.2877	0.143859	0.020695	1159.01786	26.86893
1988.3699	0.128799	0.016589	1165.76772	26.64414
1988.4548	0.114131	0.013026	1173.28821	26.42436
19885370	0.096210	0.009256	1191.94987	26.20943
1988.7078	0.078504	0.006163	121325687	25.99921
1988.7890	0.062466	0.003902	123220108	25.79356
1988.8740	0.052215	0.002726	1234.92379	2559235
1988.9562	0.039911	0.001593	1245.46432	25.39543

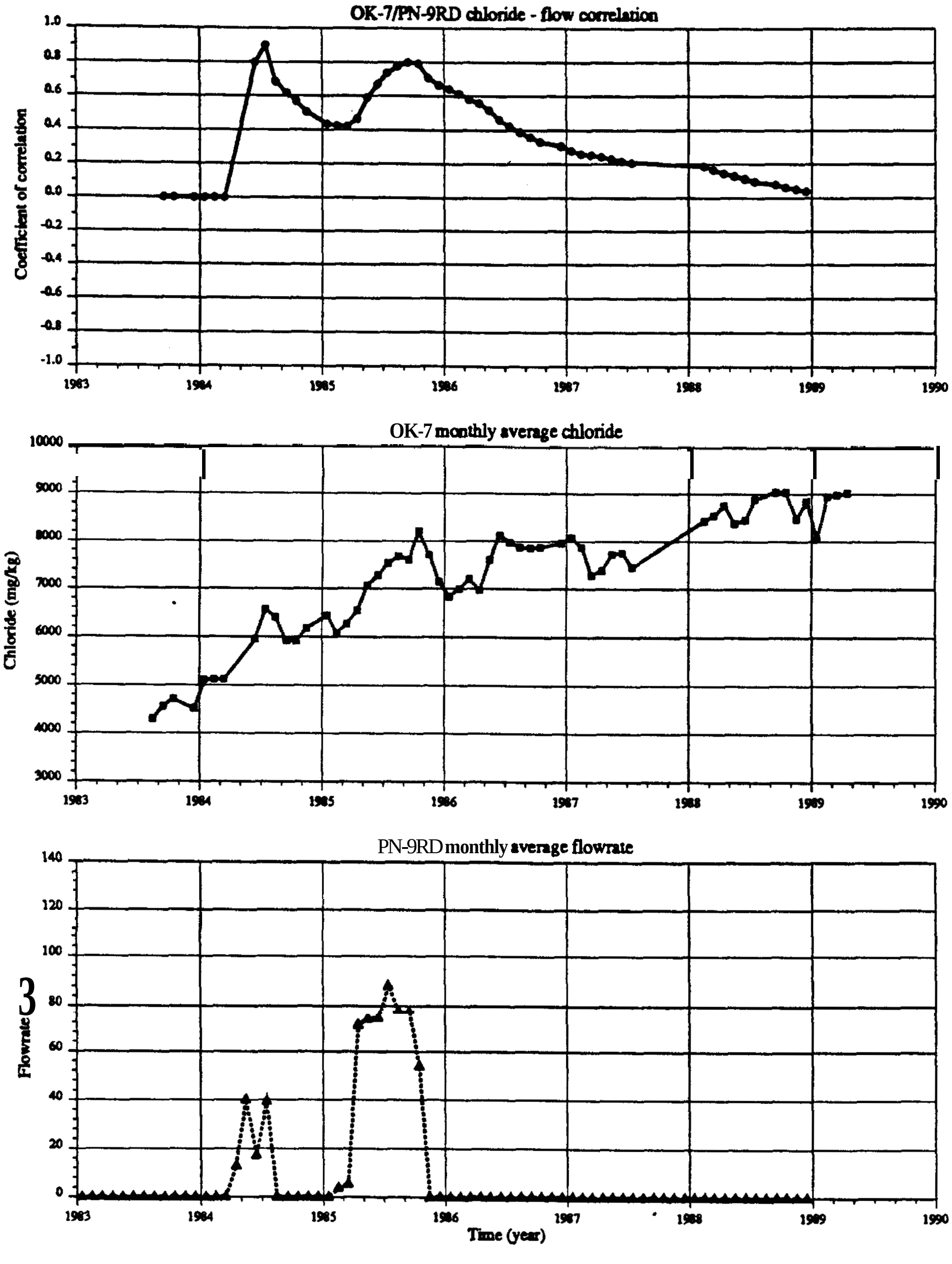


Figure *5.6:* Chloride-flow correlation method on OK-7/PN-9RD.

Table 5.2: PN-9RD selected coefficients of correlation.

PN-9RD Tracer Test Ranking	:	production Well	Minimum (*After* injection)	Maximum (Prior to Curtailment)
OK-7	:	OK-7	0.70	0.85
PN-26	:	PN-16D	0.66	0.90
PN-28	:	PN-26	0.51	0.71
PN-29D	:	PN-28	0.36	0.53
PN-18D	:	PN-18D	0.23	0.31
PN-23D	:	PN-17D	0.19	0.43
PN-16D	:	PN-23D	0.15	0.47
PN-19D	:	OK-1OD	-0.05	-0.10

0.85.

The same procedure has been applied to most of the wells for the PN-9RD tracer test. The result, using the chloride values given by Figure 5.1 and the PN-9RD flowrate, is shown in Figure 5.7. (For individual plots of all chloride-flow correlations, the reader is referred to Appendix F).

It is striking to see in Figure 5.7 how similar the shapes are for these wells. All of them, except for OK-10D, reflect the increasing correlation during the times of PN-9RD utilization, with maximum coefficients coincidental to the times prior to PN-9RD's curtailment. These coefficients before and after PN-9RD use is given by Table 5.2. Of these wells, OK-7, PN-16D, PN-18D, PN-23D, PN-26, and PN-28 responded positively in varying degrees during the PN-9RD tracer test. It can be seen that, except for the appearance of PN-16D, the order of increasing coefficients parallels that of the PN-9RD tracer test ranking based on decreasing mean transit arrival.

The case for PN-17D is different since the tracer counting methods give conflicting results (Urbino et al. 1986). The first two counting methods, employing both the ratemeter-field sample and the MCA (multi-channel analyzer)-sample

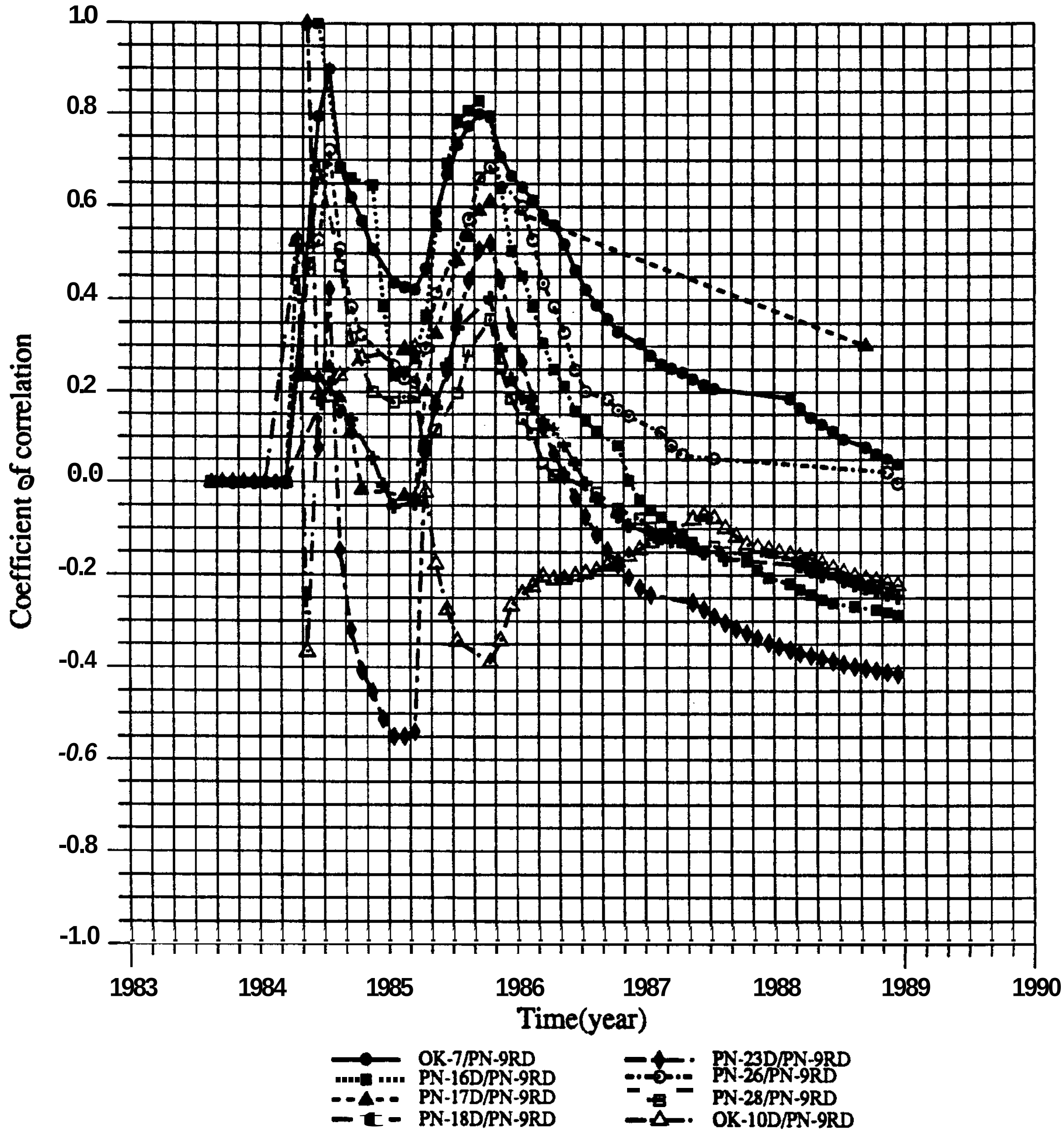


Figure 5.7: PN-9RD tracer test: chloride - flow correlation.

liquid evaporation, failed to detect returns into PN-17D. However, the alternative method of extracting silver iodide from the field sample and counting the sample by use of **MCA,** had shown positive response of PN-17D. Since the last counting method improves sensitivity due to much lower levels of detection, it is the author's opinion that there was, indeed, positive return of the radioactive tracer into PN-17D althoughs in very small amounts. This would confirm the result of the precursor PN-9RD sodium fluorescein tracer test, which showed breakthrough of the chemical dye into PN-17D after six days.

Hence, the reliability of the silver iodide extraction method during the PN-9RD test has been established and the findings of the sodium fluorescein tracer test substantiated by the results of the PN-17D/PN-9RD chloride-flowrate correlation.

In summary, this section has demonstrated that the chloride-flow correlation method apparently works by reproducing the general trend of the results of the PN-9RD tracer test.

5.1.2 Chloride Shift - Flowrate Correlation

The previous section has section has noted the apparent shift in the maximum chloride value of OK-7 when compared to the maximum injection of PN-9RD. To accommodate the reasoning that the increase in chloride change is an effect, and that there could be a lag or delay in the the response of the producing well, the producer/injector correlation was calculated with a shift in the chloride values. The chloride values were shifted by a month, two months, and sometimes by three months. The effect of doing so is illustrated by Figure 5.8. A selection of the results is given by Figure **5.9** while more plots of the method are shown in Appendix G.

Figure ***5.8*** shows that while maintaining relatively the same trend **as** for the unshifted correlation, the OK-7/PN-9RD correlations decrease in value with increasing shifts in production chloride. With a shift in chloride data, there is

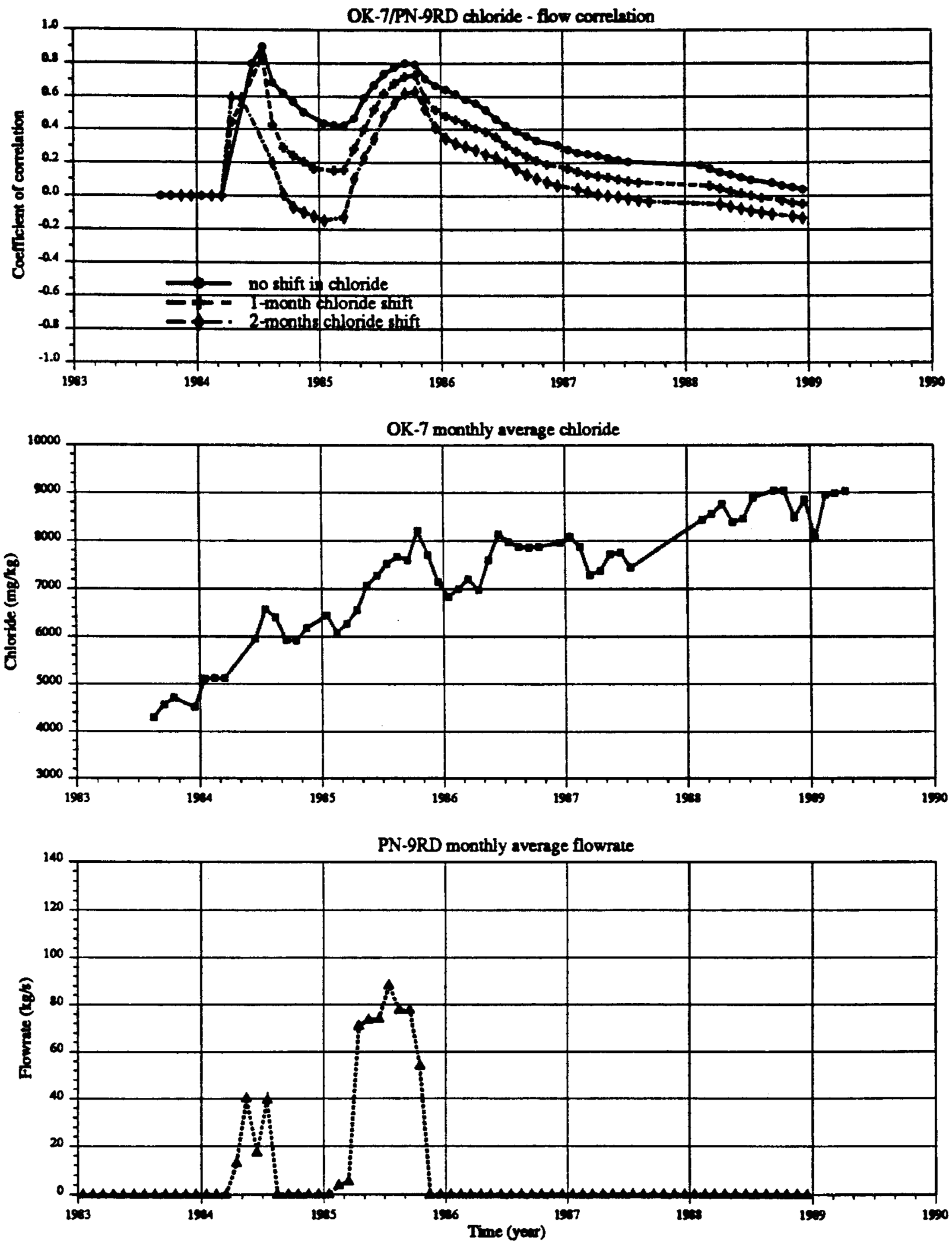


Figure 5.8: OK-7/PN-9RD chloride shift-correlation method.

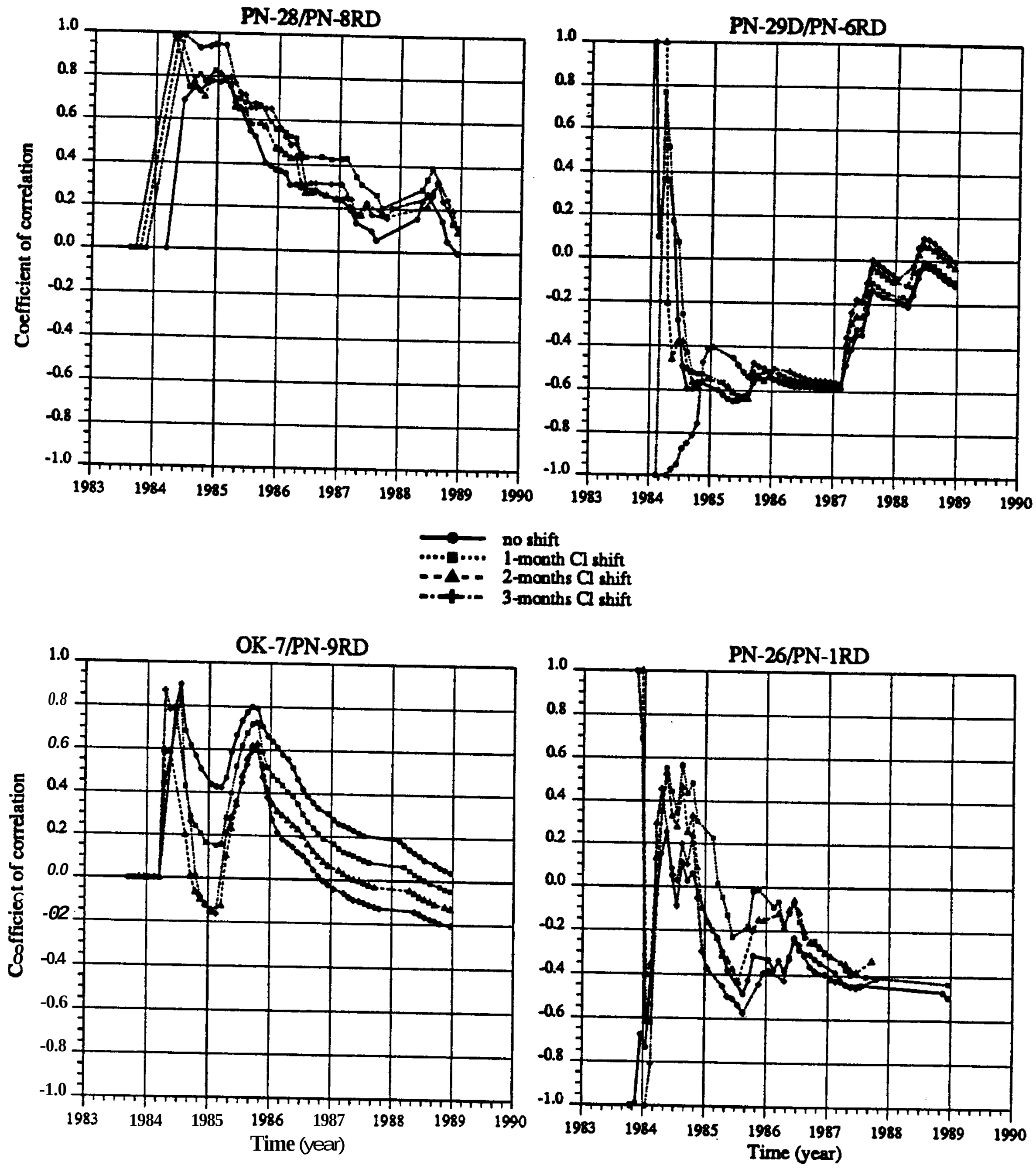


Figure **5.9:** Correlation of injection flowrate with shift in chloride.

also a shift in the maximum coefficients for the second hump or wave. Hence, while the maximum was 0.80 on September 1985 for the unshifted correlation, these were reduced to 0.73 on October 1985 for a one-month chloride shift. However, a two-month or three-month shift in chloride value does not shift the maximum by the same degree as the one-month shift. Hence, a two-month shift has a maximum of 0.63 on October 1985, and a three-month chloride shift has a maximum of 0.60 also on the same month.

This is the general trend for most of the chloride shifts as can be seen from the figures in Appendix G. However, there are some exceptions to this trend. Correlations of OK-7 with injection wells PN-1RD, PN-2RD, and PN-3RD, for the most part, are greater with shifts in chloride of OK-7. While the usual increase in the coefficients of 0.2 may not be sufficient to alter the prevailing correlation, sometimes the effect would be significant to do otherwise. As an example, correlations of OK-7 with PN-1RD and PN-2RD increase tremendously from negative correlations to high positive correlations in the first fifth of the curve. Such is the case, too, for the PN-26/PN-1RD and PN-28/PN-1RD correlations.

Since the correlation trends with chloride shift do not significantly depart from that with no shift, it would suffice to simply use the coefficients of correlation for no chloride shift.

5.1.3 OK-12RD/PN-6RD Tracer Test Application

Figure 5.10 shows the injection flowrates of wells PN-6RD and the increases in the reservoir chloride of well PN-17D. Figure 5.11 includes the result of finding the correlation between the chloride data of PN-17D and the injection flowrates of PN-6RD.

Due to the unavailability of data on injection well OK-12RD, PN-6RD was used in its place on the basis of the sodium fluorescein test on OK-12RD which exhibited the unequivocal return of the dye on PN-6RD. (see Table 3.1). The premise, then, is that a well which interacts with OK-12RD would interact with

PN-6RD due to the strong communication between the two.

From Figure 5.10, it can be gleamed that PN-6RD was injecting for four intervals of time: from Sept 1983-May 1984, from Nov 1984-Jan 1985, from Mar-Aug 1987 and from Apr- 1988. There are also two other brief periods which are Sept 1985 and Dec 1987. An inspection of the injection flowrates from Appendix E would show that for the latter periods of PN-6RD injection, only PN-1RD injection comes close to the PN-6RD plot. However, in both instances the start and end of injection into PN-6RD occurs before that of PN-1RD (*e.g.* Mar-Aug 1987 for PN-6RD as oppose to Jun-Nov 1987 for PN-1RD). There was also PN-8RD which was injecting from Oct 1987 - Aug 1988. It is important to recognize these differences in order to distinguish the effect of one injection well from that of another.

Figure 5.10 shows how similar the chloride and flowrate curves are for the first interval. The start of ascent, the decline, and the peaks coincide. This could be interpreted as signifying a strong degree of correlation between PN-17D and PN-6RD. For the second interval, the chloride values of PN-17D start to increase and decrease earlier than the hook-up of PN-6RD, hence it can be surmised that for this period other injection wells are contributing. It is, nevertheless, striking that in the brief period of Sept 1985, when PN-6RD comes on line again after eight months, the chloride values of PN-17D start to increase at the same time. However, the lack of PN-17D chloride measurements after October 1985, precludes further analysis between the two wells and necessitates other production wells, instead.

Figure 5.11 shows the chloride-flow correlation between PN-17D and PN-6RD. As discussed in the preceding paragraph, a high degree of correlation between the two wells is indicated especially in the first interval of injection. For this interval, the coefficients range from 0.58 to 0.85 where 0.63 is the coefficient prior to curtailment of PN-6RD and 0.58 after curtailment. This first interval is followed by declining coefficients because of the increasing chloride values simultaneous with the absence of injection into PN-6RD, as well as the lack of

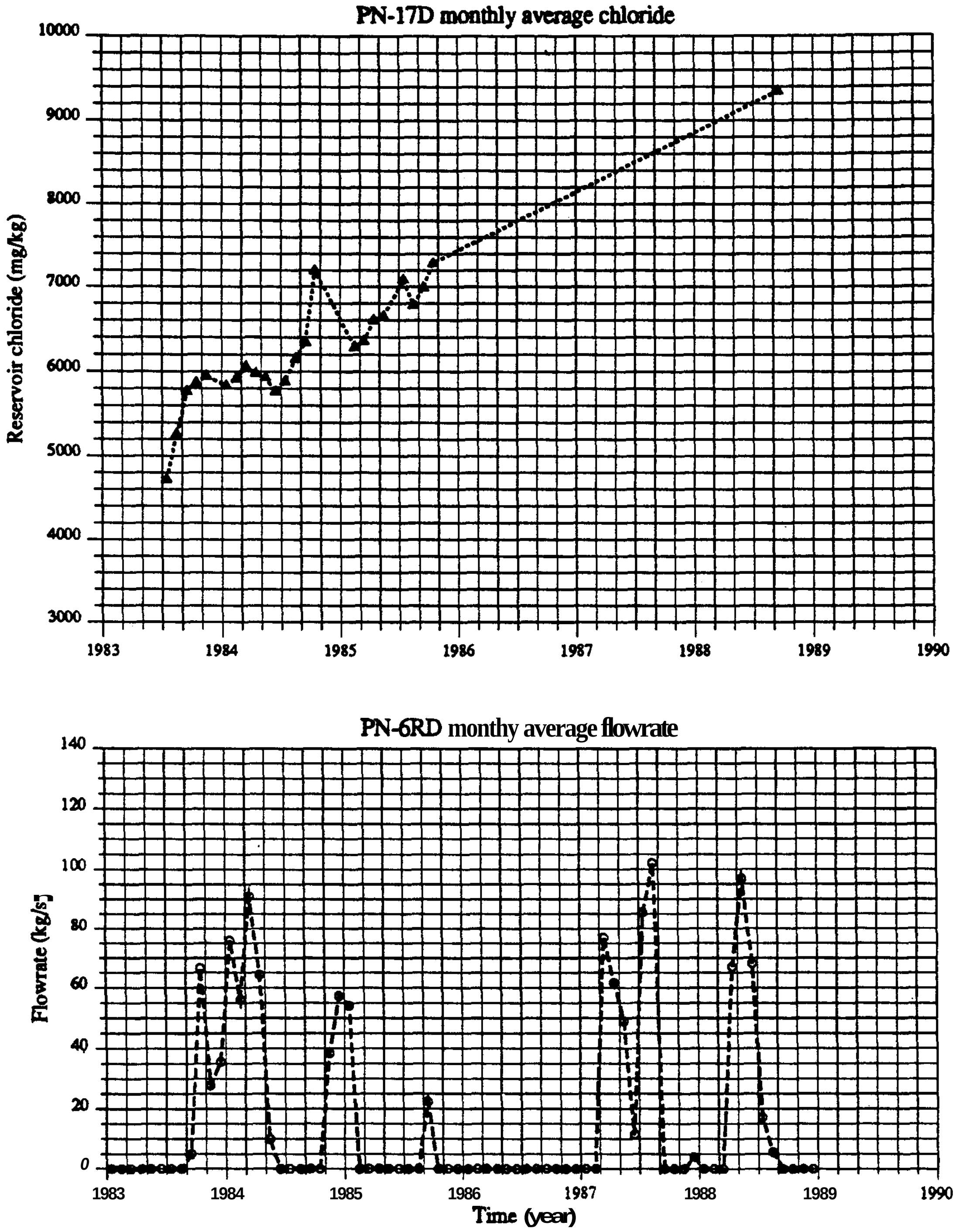


Figure 5.10: PN-17D chloride values and PN-6RD flowrate.

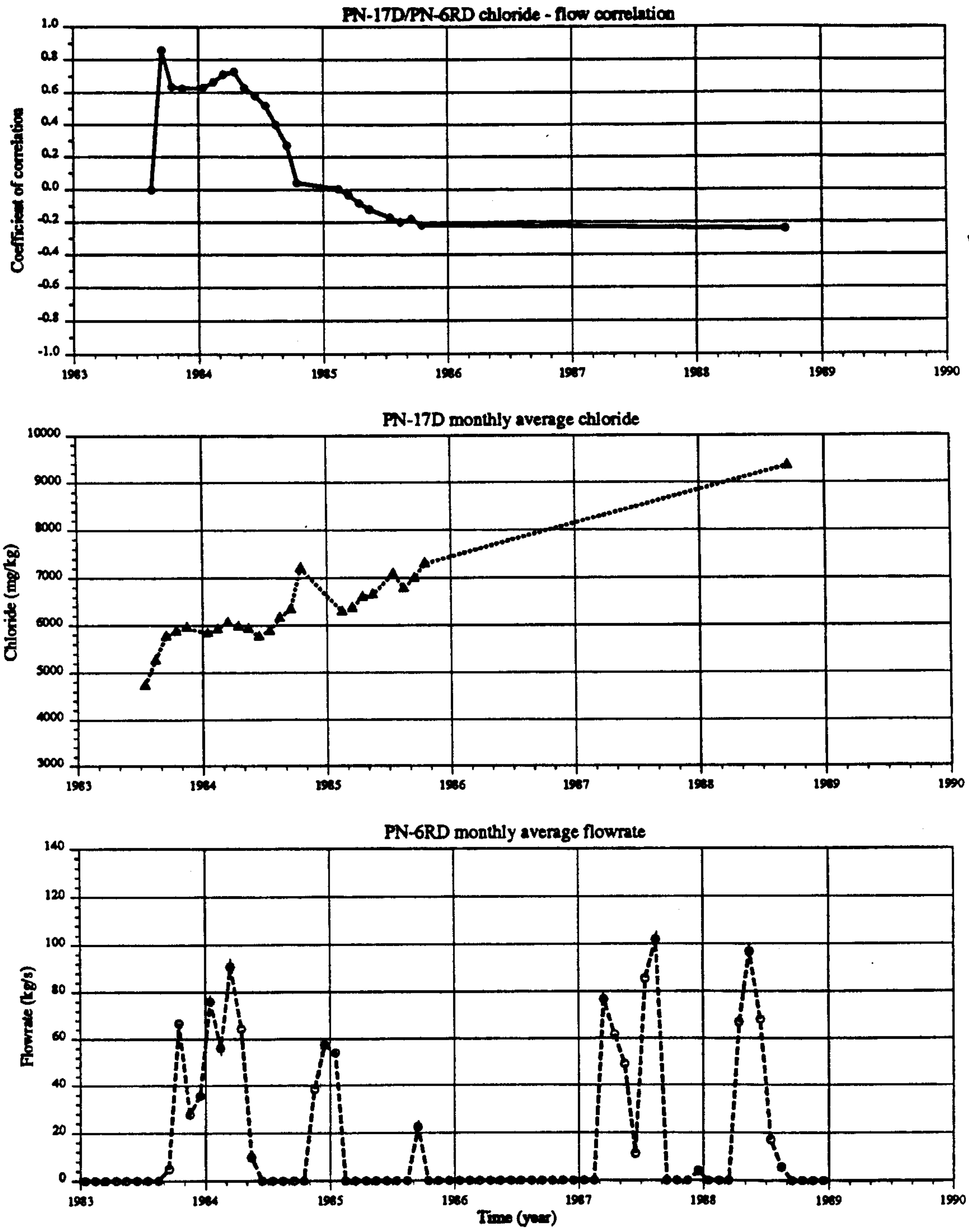


Figure 5.11: Chloride-flow correlation method on PN-17D/PN-6RD.

further measurements on PN-17D in the latter period.

The correlation of PN-6RD with other production wells monitored during the OK-12RD tracer test was calculated, and the results are plotted in Figure 5.12. As listed in Table 3.1, the wells which responded positively during the OK-12RD tracer test are PN-17D, OK-10D, OK-7, PN-28, and PN-15D ranked according to percentage of tracer return. Traces were also found in PN-21D and PN-26.

Some points are worth noting in Figure 5.12 if the diagram is visualized as being divided into strips corresponding to the intervals when PN-6RD is injecting (Sep 83-May 84, Nov 84-Jan 85, Mar-Aug 87, and Apr-Jul 88).

- First, the high coefficients of correlation (0.46-0.99) are evident in the first interval corresponding to PN-6RD injection. A comparison between the ranking provided by the OK-12RD tracer test and the selected coefficients in this first interval is provided by Table 5.3. This table shows a high degree of correlation of PN-6RD with PN-28, OK-10D, OK-7, PN-26, PN-17D, PN-15D, and PN-21D on the basis of the maximum value of coefficients coincident with maximum injection into PN-6RD during this period. If the criterion has been based on the correlation after PN-6RD injection, then the ranking would be shifted to PN-17D, PN-15D, PN-28, PN-26, OK-7, and OK-10D. Although the method does not provide an exact duplicate of the tracer test ranking, it affirms the strong communication between these pair of wells.
- Second, most of the correlations decrease because PN-6RD was cut-off from the line. It can also be attributed to the scarcity of chloride measurements on the producing well during certain time intervals. Nevertheless, from Figure 5.12, it is very striking to see that in the next three intervals of time (Nov 84-Jan 85, Mar-Aug 87, and Apr-Jul 88) during which PN-6RD was injecting, the correlations of OK-7, PN-28, and PN-26 register a dramatic change in their trends and correlations start increasing. The start and end of these gradients correspond exactly with the onset and termination of PN-6RD injection. Even the effect of the brief injection on Sept 1985 was

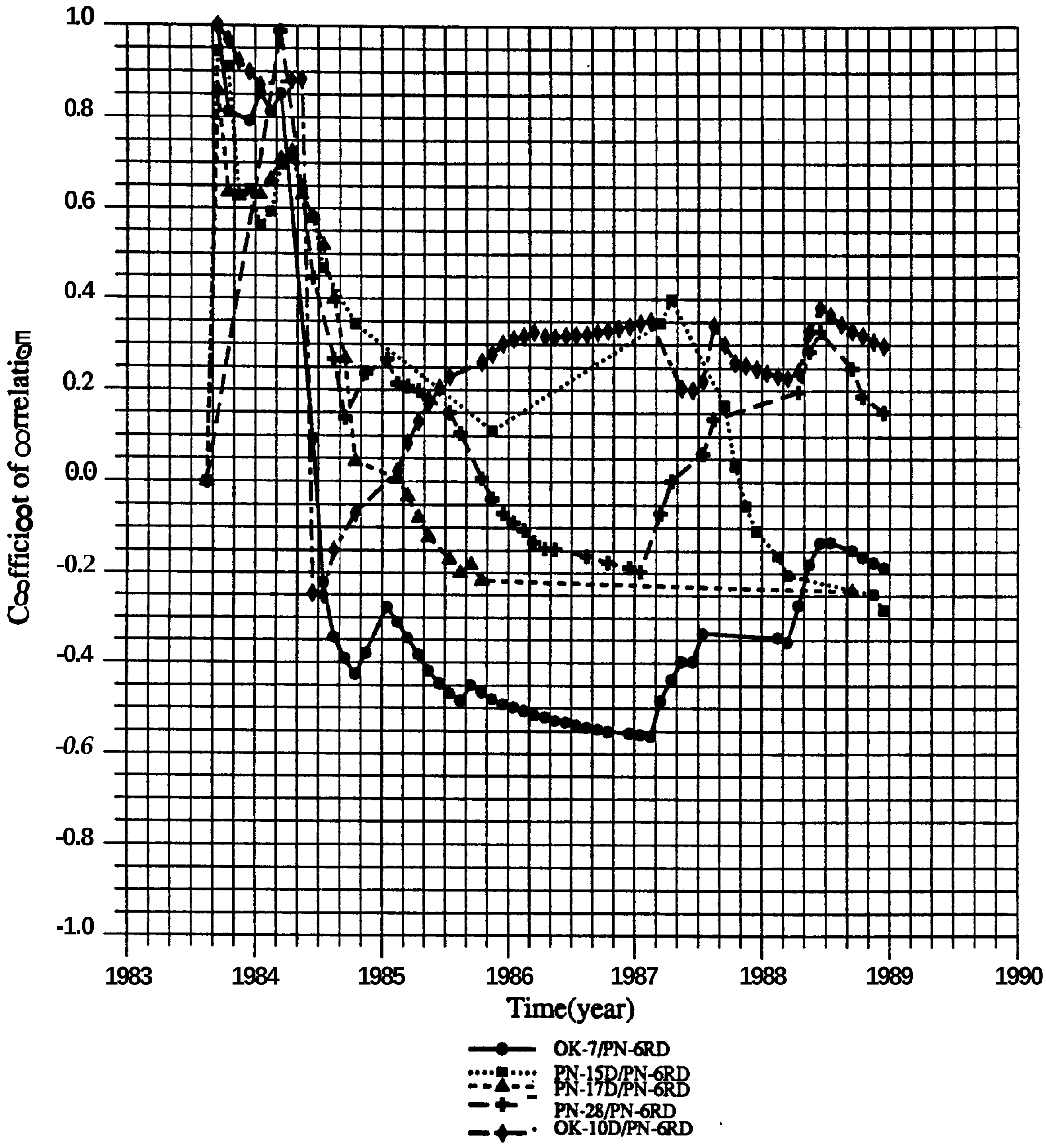


Figure 5.12: OK-12RD/PN-6RD tracer test: chloride-flow correlation.

Table 5.3: OK-12RD/PN-6RD selected correlation for first time interval.

OK-12RD Tracer Test Ranking	Production Well	Minimum (After injection)	Maximum * (Prior to curtailment)
PN-17D	PN-28	0.45	0.99
OK-10D	OK-10D	-0.25	0.88
OK-7	OK-7	0.09	0.85
PN-28	PN-26	0.11	0.78
PN-15D	PN-17D	0.58	0.71
PN-26	PN-15D	0.58	0.70
PN-21D	PN-21D	-	-

*taken for data on Mar 1984 with maximum injection

manifested by wells OK-7, PN-26, and PN-17D. In the last interval of PN-6RD injection (Apr-Jul 88) all the wells took a sudden turn and exhibited increasing correlations which lasted until PN-6RD was curtailed. It can only be inferred, therefore, that these changes can be ascribed to a high degree of relationship of these producing wells with PN-6RD.

5.1.4 Other Production/Reinjection Correlations

To ascertain the inference from the preceding sections that the chloride-flow correlation method is able to reproduce the positive relationship of the OK-12RD/PN-6RD tracer tests, the correlations of PN-6RD with the other Palinpinon production wells were calculated and plotted in Figure 5.13. From Figure 5.13, it can be seen that the behavior or characteristic previously exhibited by the wells with positive return in the OK-12RD tracer test, *are also manifested* by most of the production wells. As an example, PN-16D, and PN-23D are production wells directed to the south while PN-30D and PN-19D are wells directed to the southwest and west, respectively. Though these wells

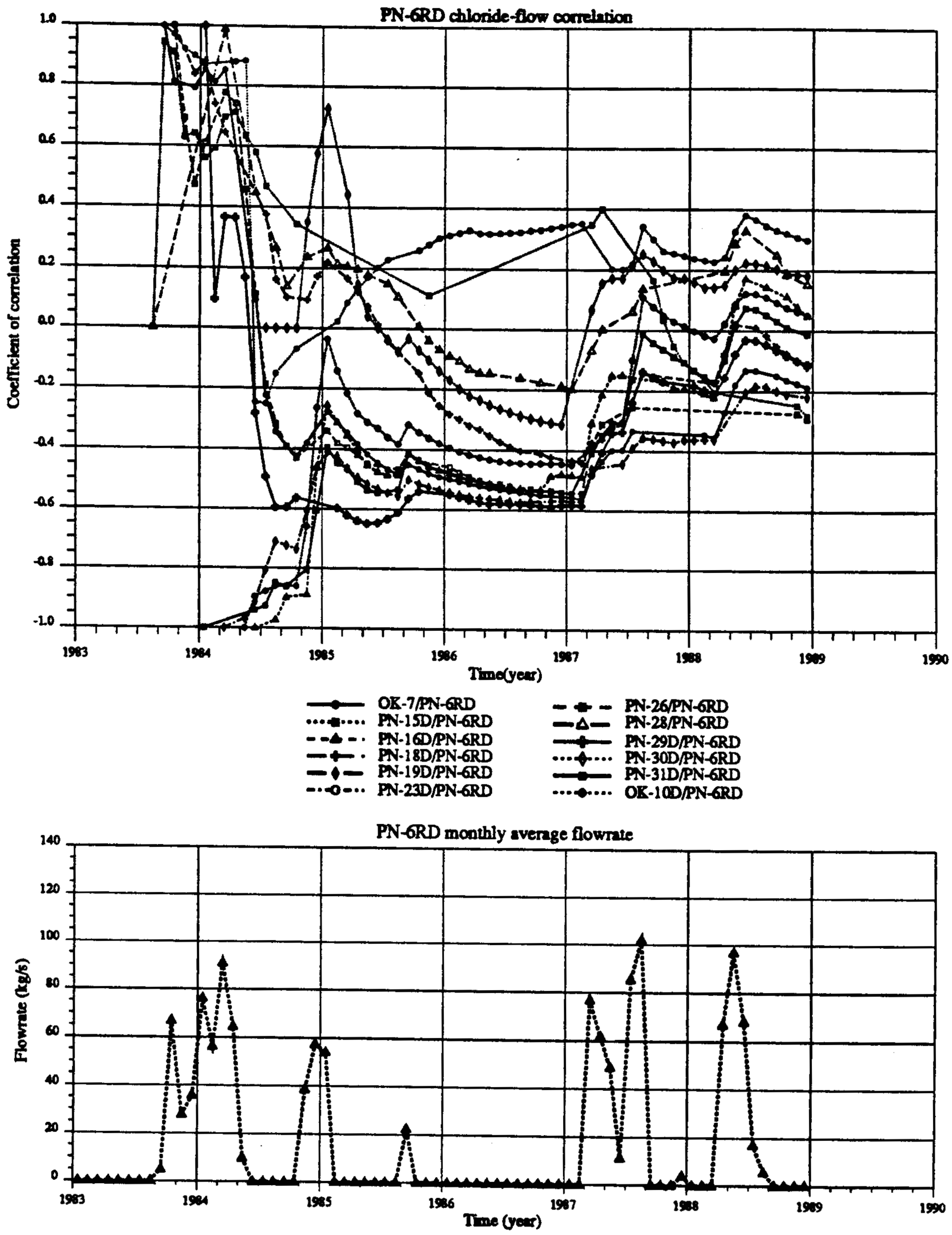


Figure 5.13: PN-6RD correlation with other wells.

were not monitored during the OK-12RD tracer test because they were not producing, subsurface studies on the basis of well-fault intersections (Urbino et al., 1986) imply minimal communication between these aforementioned wells and PN-6RD. However, as seen from Figure 5.13, these wells' correlation with PN-6RD appear to be as sensitive to the changes in PN-6RD injection as those wells with positive return. To investigate this further, the correlations of the other injection wells with selected Palinpinon wells were determined and plotted together with the injection well utilization as shown in Figures 5.14 to 5.21.

From Figures 5.14 to 5.21, the following aspects are worth noting:

- In general, most of the correlation plots follow the trend of the injection well curve. Correlations increase when the injection well is put on line and decrease when the injection well is taken out. The points of prominent local maxima and minima of the correlation plots usually coincide with those of the injection wells'.
- At first glance, the correlation plots indicate that reinjection wells PN-3RD, PN-5RD, PN-4RD, PN-SRD, PN-SRD, and PN-7RD correlate highly and positively with production wells while PN-1RD, PN-2RD, and PN-6RD correlate negatively.
- The plots seem to indicate that intermittent use of the injection well as in the case of PN-1RD and PN-6RD usually produces low correlations especially in later times due to the contribution of more data points in the calculation. Hence, it can be seen that the initial correlations of PN-1RD, PN-2RD, PN-4RD, PN-GRD, PN-7RD, PN-SRD, and PN-9RD are usually high, although for wells PN-1RD and PN-2RD, there is a wider spread of values. On the contrary, PN-3RD, PN-4RD, and PN-5RD had maintained relatively high correlations.
- The correlation plots of OK-1OD usually run counter to the general trend of the rest of the production wells. This demonstrates that OK-1OD behaves quite differently from the others in terms of chloride increases as can be seen from Figure 5.1.

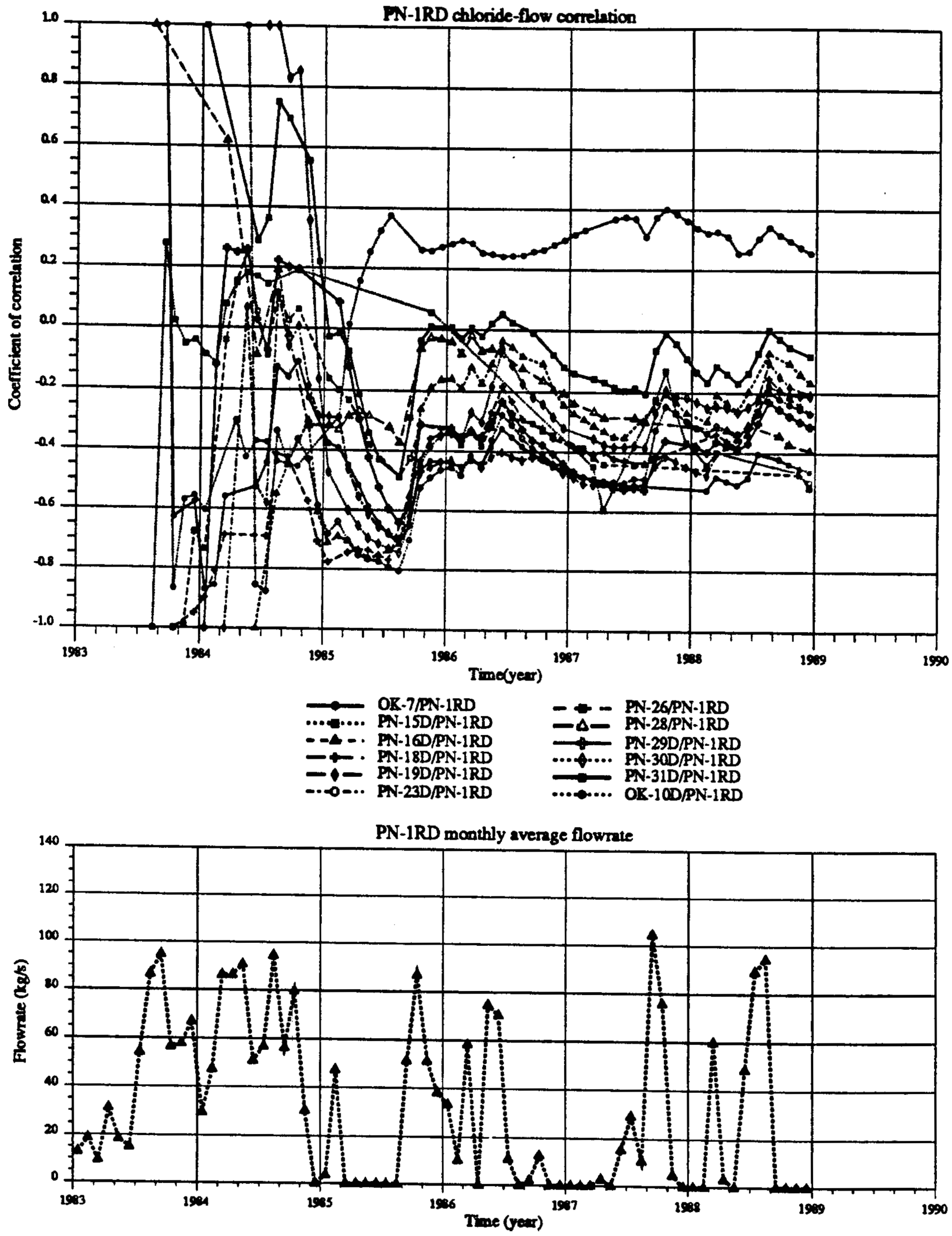


Figure 5.14: PN-1RD correlation with other wells.

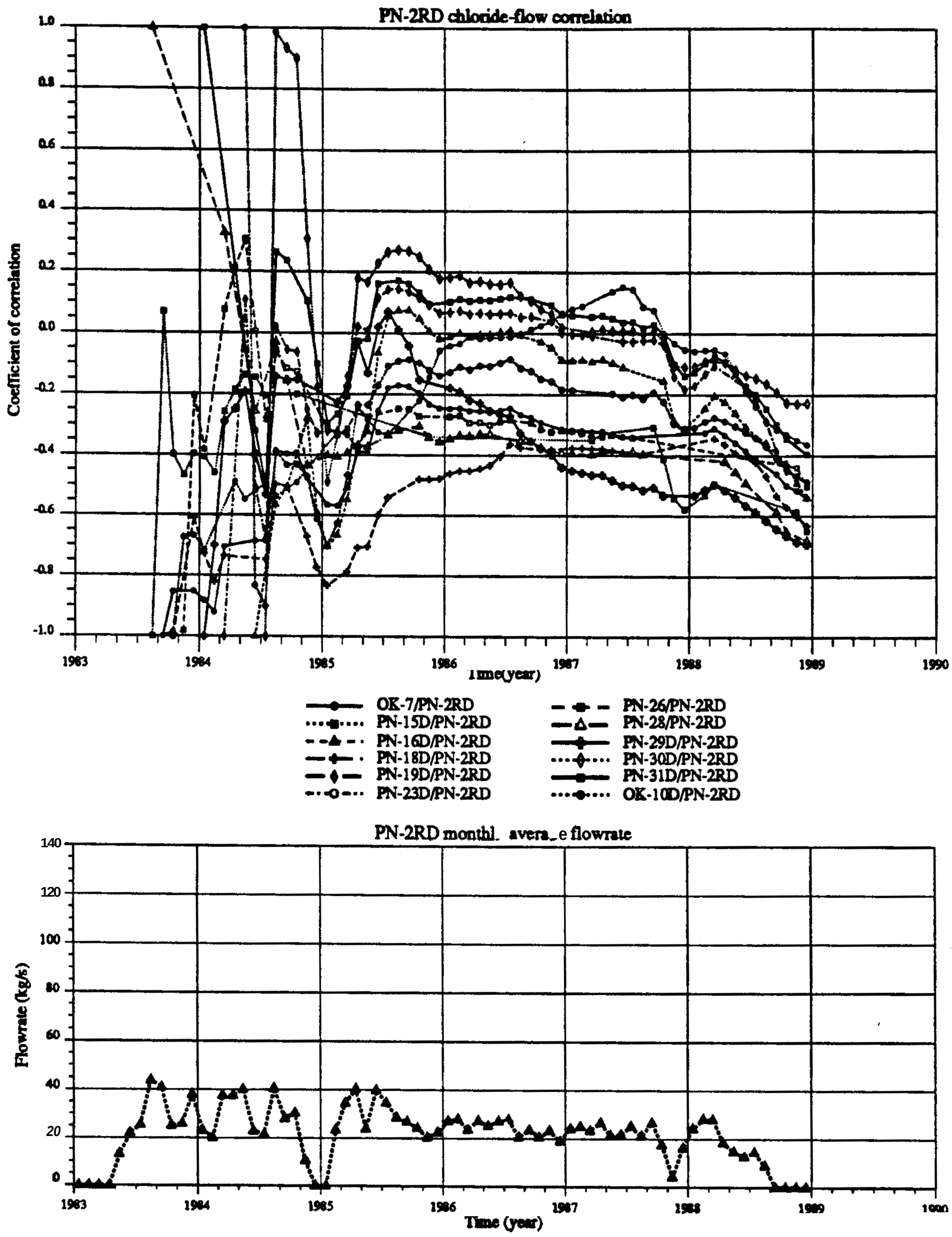


Figure 5.15: PN-2RD correlation with other wells.

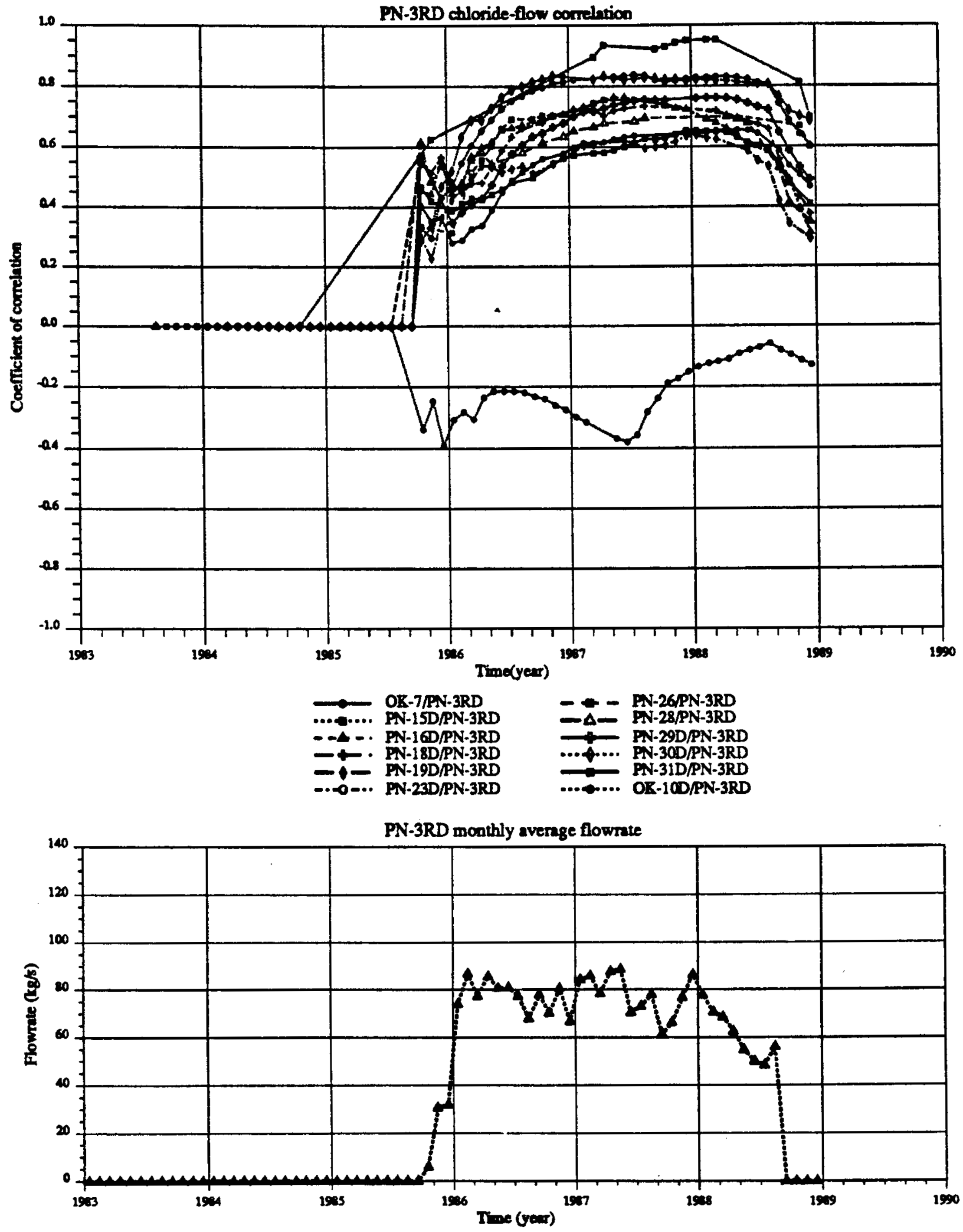


Figure 5.16: PN-3RD correlation with other wells.

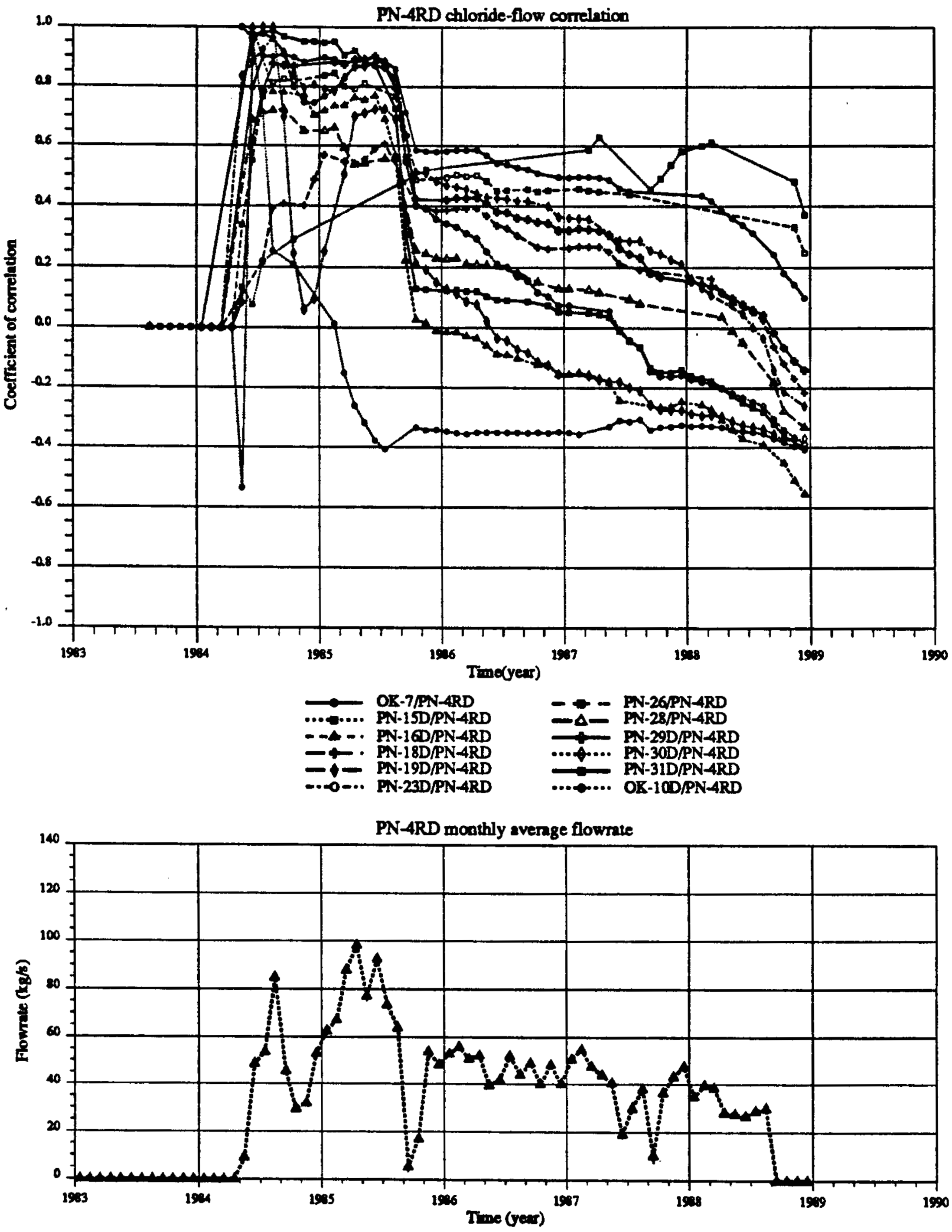


Figure 5.17: PN-4RD correlation with other wells.

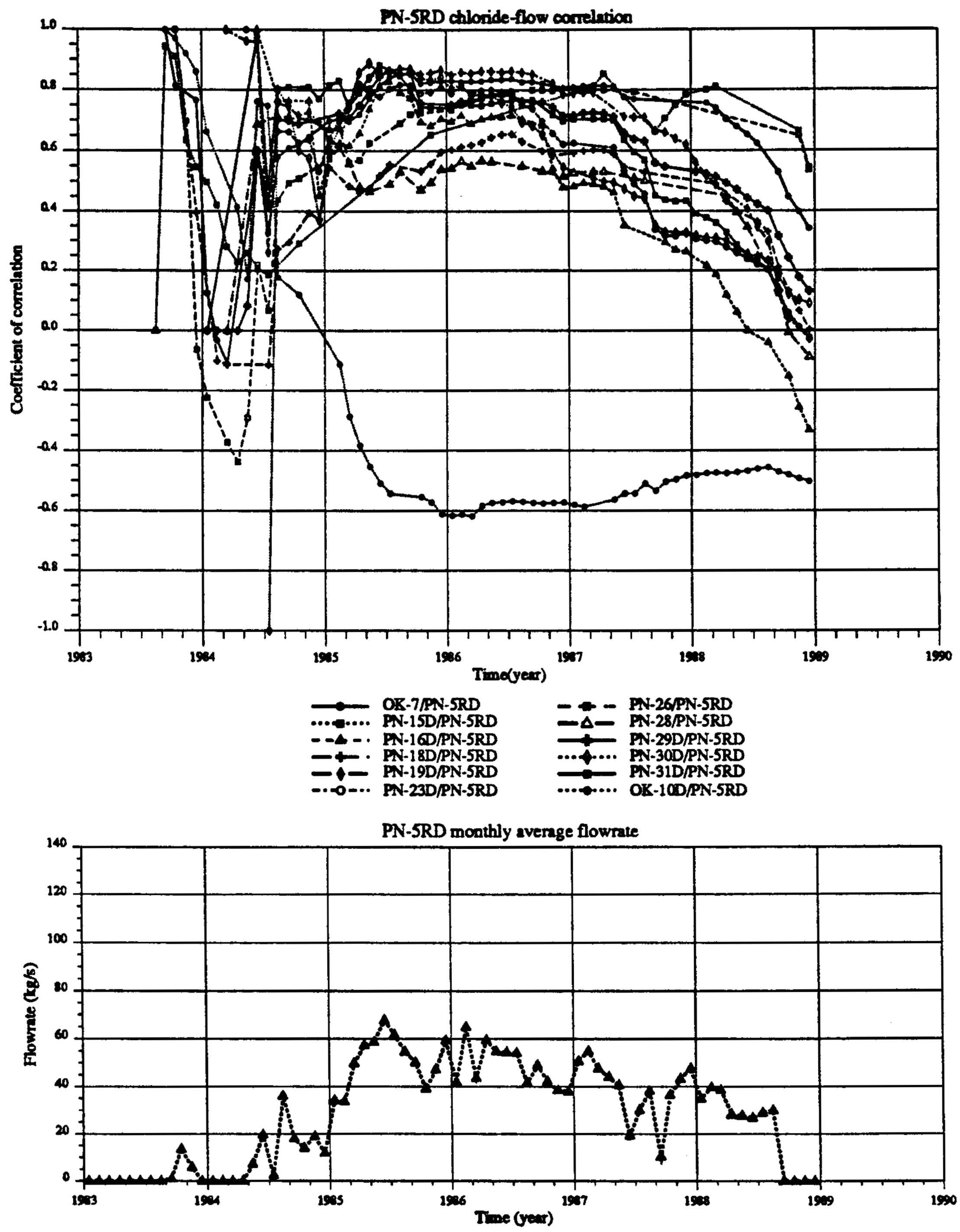


Figure 5.18: PN-5RD correlation with other wells.

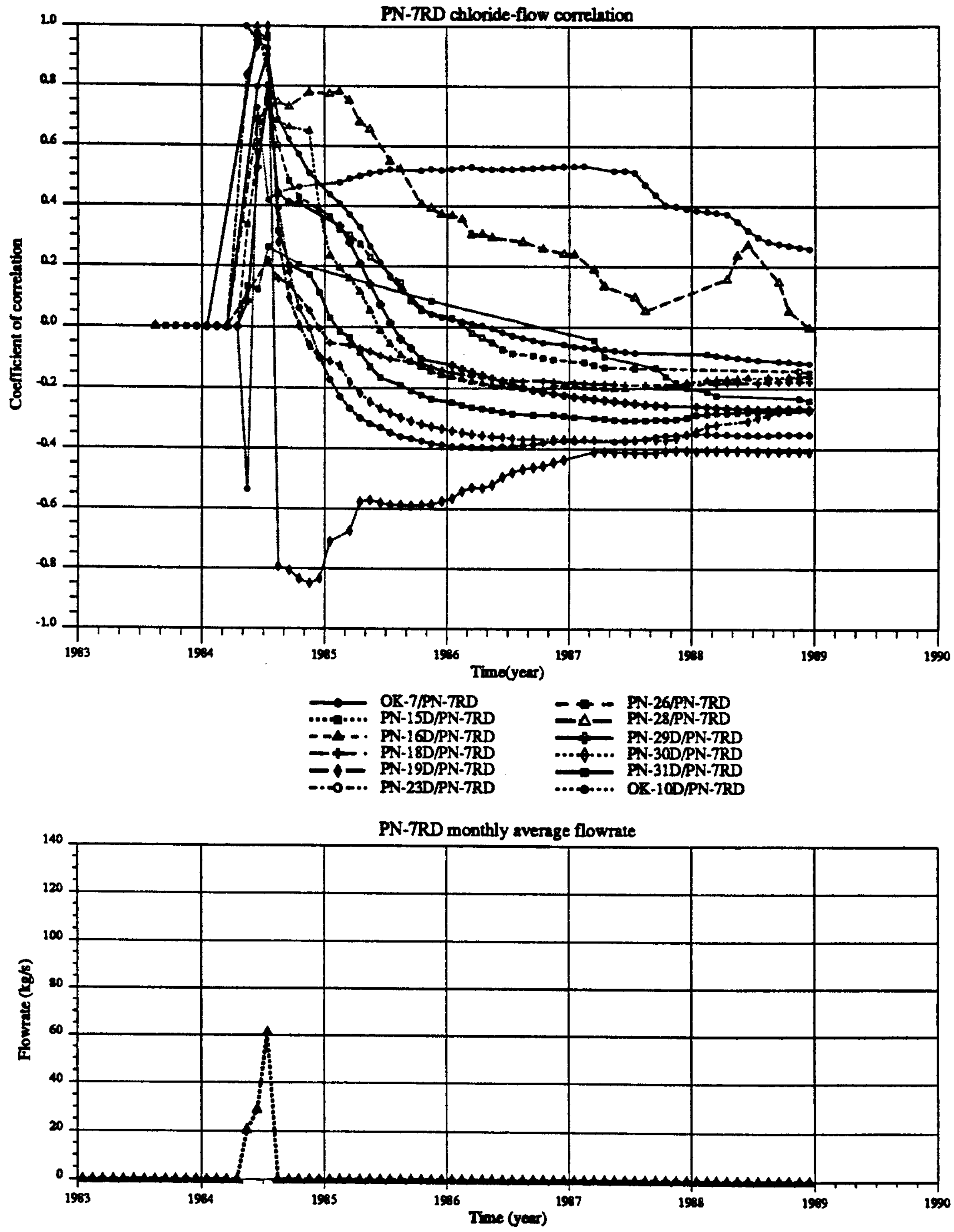


Figure 5.19: PN-7RD correlation with other wells.

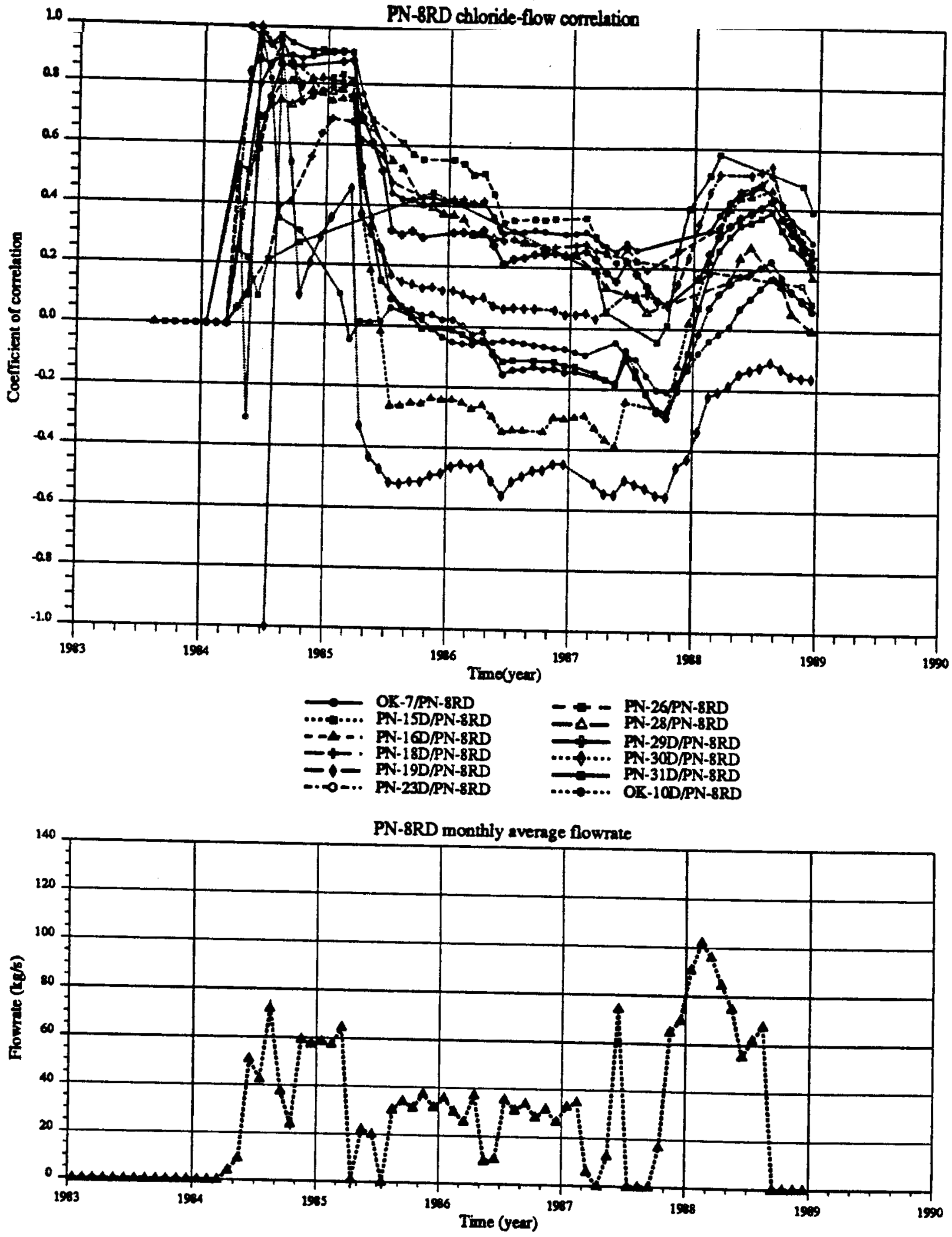


Figure 5.20: PN-8RD **correlation with other wells.**

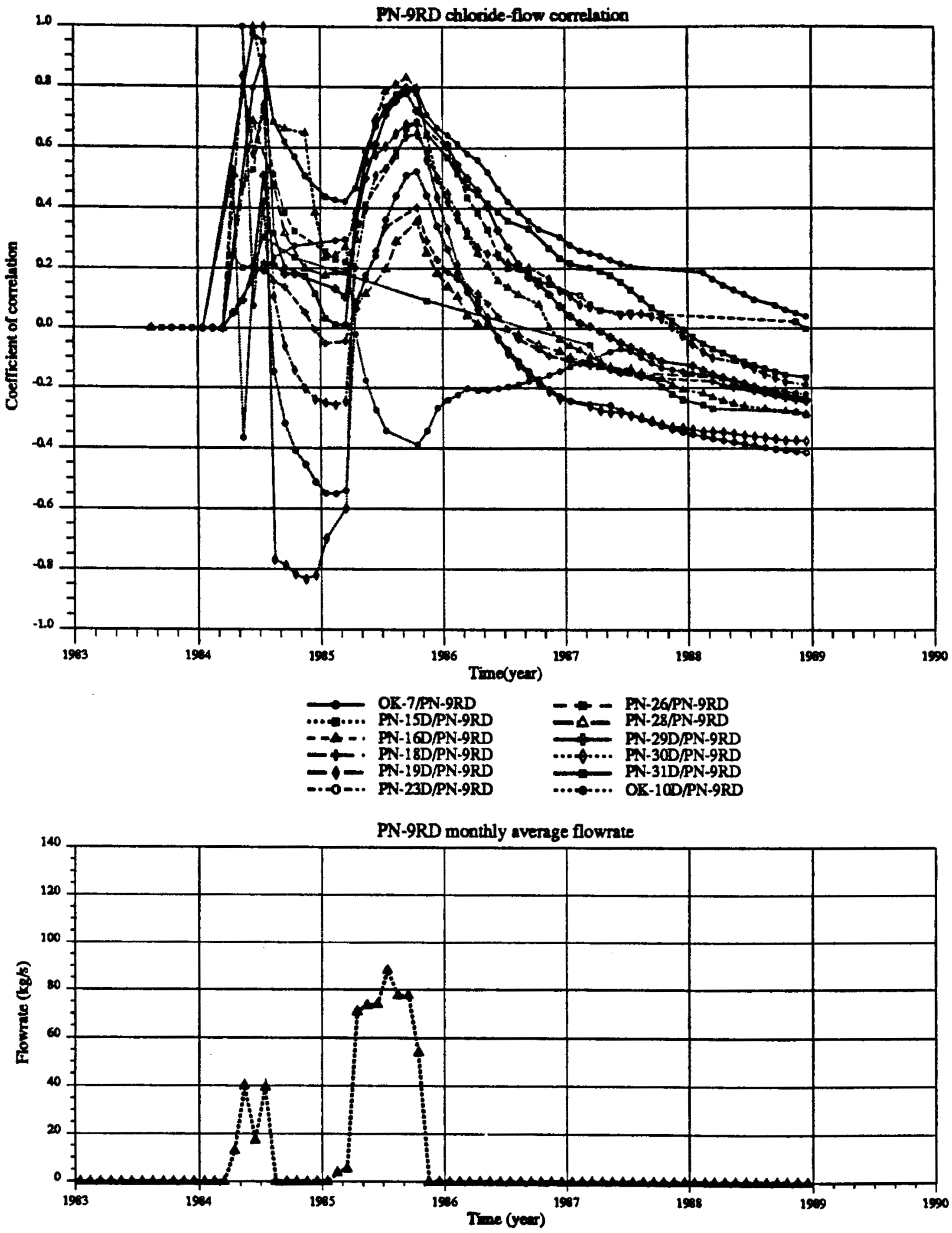


Figure 5.21: PN-9RD correlation with other wells.

Table **5.4:** Representative coefficients of chloride-flow correlation.

Production Well	PN-1RD	PN-2RD	PN-3RD	PN-4RD	PN-SRD	PN-6RD	PN-7RD	PN-8RD	PN-9RD
OK-10D	0.375	-0.282	-0.152	-0.378	-0.587	0.328	0.419	0.169	-0389
OK-7	-0.124	-0.170	0.656	0.901	0.814	-0.180	0.905	0.475	0.802
OK-9D	-0.357	-0.551	0.662	0523	0.280	0.425	0.286	0.101	0.142
PN-14	-0.157	-0.894	0.768	0.070	0.677	-0.120	ins data	0.957	ins data
PN-15D	0.192	-0.136	0.950	0.594	0.809	0.170	0.262	0581	0.304
PN-16D	-0.159	0.075	0.723	0.771	0.493	0.173	ins data	0.462	0.832
PN-17D	0.182	0.056	ins data	0.503	0.7 10	ins data	0.163	ins data	0.61 1
PN-18D	-0.413	-0.363	0.735	0588	0.601	0.021	0219	0515	0.404
PN-19D	0.114	0.145	0.635	0.881	0.791	-0.182	0.973	0.542	0.647
PN-21D	0.551	-0.495	-0.572	-0332	-0.358	-0.102	insdata	0.797	insdata
PN-23D	-0.336	-0.100	0.830	0.870	0.610	0.122	0.926	0.227	0523
PN-24D	insdata	0251	0.769	0.721	0.791	0.147	0.557	0.597	0.864
PN-26	0.115	0.306	0.755	0.793	0.804	-0.250	0.801	0.370	0.685
PN-27D	-0.012	-0.190	0.780	0.879	0.8 12	-0.200	0.807	0.47 1	0.7 17
PN-28	0.192	-0.330	0.700	0539	0.527	0.286	0.746	0.272	0358
PN-29D	0.224	0.071	0.762	0.901	0.724	-0.029	0.076	0.428	0.782
PN-30D	insdata	0.272	0.822	0.725	0511	0.222	insdata	-0.108	0.682
PN-31D	0.750	0.172	0.654	0.873	0.705	0.074	0.959	0.390	0.7%
Dates Taken	Oct-83 Aug-84	May-84 Jun-84	Dec-87	Apr-84 JUD-84	Feb-87	Aug-87 May-88	Jd-84	Aug-88	Jd-85

*ins data refers to insufficient data points caused by the absence of either injection or chloride values in the time interval considered.

- Although correlation trends are similar, it is believed that the relative heights of the individual plots indicate a degree of the production/injection interaction or relationship. On this premise, the correlation of the production wells during the time of maximum injection were chosen to be representative of the production/injection relationship. These values are listed in Table 5.4.

It will be noted that in Table 5.4 that there is a large margin on the dates when these correlations were taken. This poses a difficulty in comparing the relative ranking of the injection wells for a certain production wells (laterally or horizontally). However, it could be used for ranking the producing wells for a certain injection well (vertically). As an example, though the correlations for PN-1RD, PN-2RD, PN-4RD, PN-7RD, and PN-9RD, were taken in the years 1983-85, the correlations for PN-3RD, PN-6RD, and PN-8RD were taken in the latter years of 1987-88. This is due to the different periods of utilizing the reinjection wells. As a result, in the OK-7 row, it would not be possible to say that for OK-7, PN-4RD communicates stronger than PN-8RD since the coefficients were taken at disparate different times. But a look at the PN-9RD column would show the ranking to be PN-24D, PN-16D, OK-7, PN-31D, PN-29D, PN-27D, PN-26, PN-SOD, PN-19D, PN-17D, PN-18D, PN-28, PN-16D, OK-9D and finally, OK-1OD in order of decreasing correlation. These results would indicate that PN-24D, PN-16D, and PN-27D are three. other wells which correlate highly with PN-9RD aside from the wells monitored to do so during the PN-9RD tracer test. In the same fashion, the PN-1RD column would indicate that the wells which correlate positively with it are PN-31D, PN-29D, PN-28, PN-15D, PN-17D, PN-26, and PN-19D. However, though these wells were monitored in the sodium fluorescein test (see Table 3.1)) the dye was detected only in production wells PN-26, PN-28, and OK-7. The results, therefore, of the chloride-flow correlation are not in substantial agreement with the chemical tracer test. It will be noted that for the PN-6RD column, the ranking of wells of OK-9D, OK-10D, PN-28, PN-SOD, PN-16D, PN-15D, PN-23D, and PN-31D are slightly different from the previous ranking provided by Table 5.3. The reason is that different times were considered for the two tables and of the two, Table 5.4 covers a longer span of time.

- It is evident, then, that the chloride-flow correlation method can rank production wells for each injection well but fails to rank the injection wells for each production well. In other words, the method fails to distinguish or separate the individual contributions of the injection wells for a particular production well especially when the the injection wells are used simultaneously in the same time.

5.2 Chloride - Cumulative Flowrate Correlation

Another method used was to investigate the correlation between the production chloride value and the cumulative injection flowrate. Since the chloride value of a production well at a particular time is an accumulated effect, it would seem reasonable to see the relationship between this chloride value and the cumulative flowrate of the injection well. This means that the injection flowrate is summed with time and the cumulative flowrate at any given time is correlated with the production chloride value.

Figures **5.22** and **5.23** illustrate the methods on OK-7/PN-9RD and PN-17D/PN-6RD pair of wells, while Figure **5.24** shows the results on wells **PN-26, PN-28,** and **PN-29D.** Other plots are given in Appendix H. It can be seen from Figures **5.22** and **5.23** that the correlation values of OK-7/PN-9RD and PN-17D/PN-6RD are always positive and generally high. This is affirmed by Figure **5.24** which shows consistently high positive values for the production wells regardless of the injection well correlated with. Upon examination, this can be explained by the fact that when the injection flowrates are summed, the resulting increasing flowrates are correlated with increasing chloride values, too. The outcomes, therefore, are high positive values of correlation. For this reason, this method has been disregarded as an effective tool of determining production/injection relationship.

5.3 Chloride Deviation - Flowrate Correlation

The purpose of the third method was to examine the relationship between the magnitude of the increases in the chloride value of a producing well with the injection flowrates. If there is a strong communication between a pair of producer and injector, it would be logical to expect that the effect of a high injection rate would be a greater step change in the chloride value of the

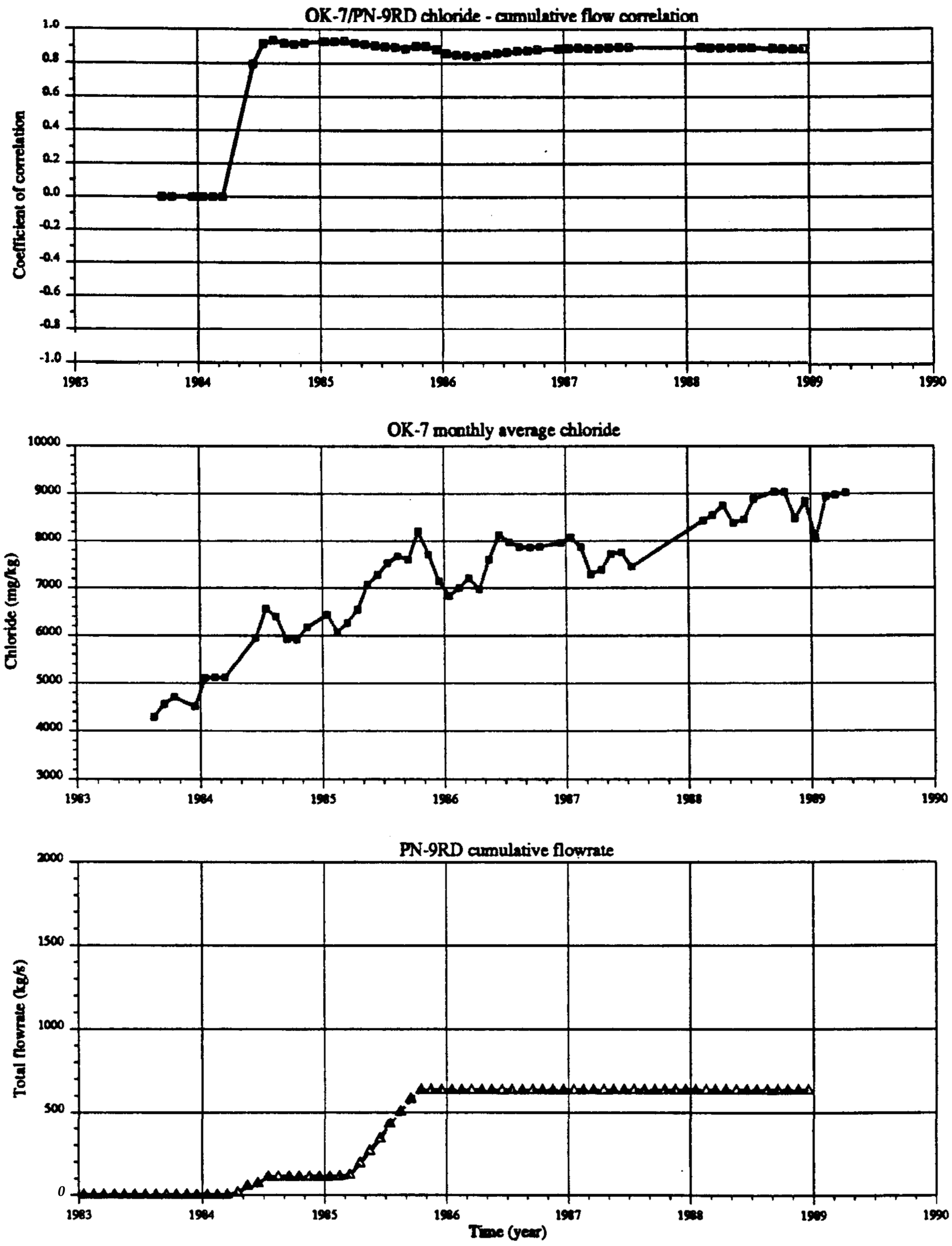


Figure 5.22: Chloride-cumulative flow correlation method on OK-7/PN-9RD.

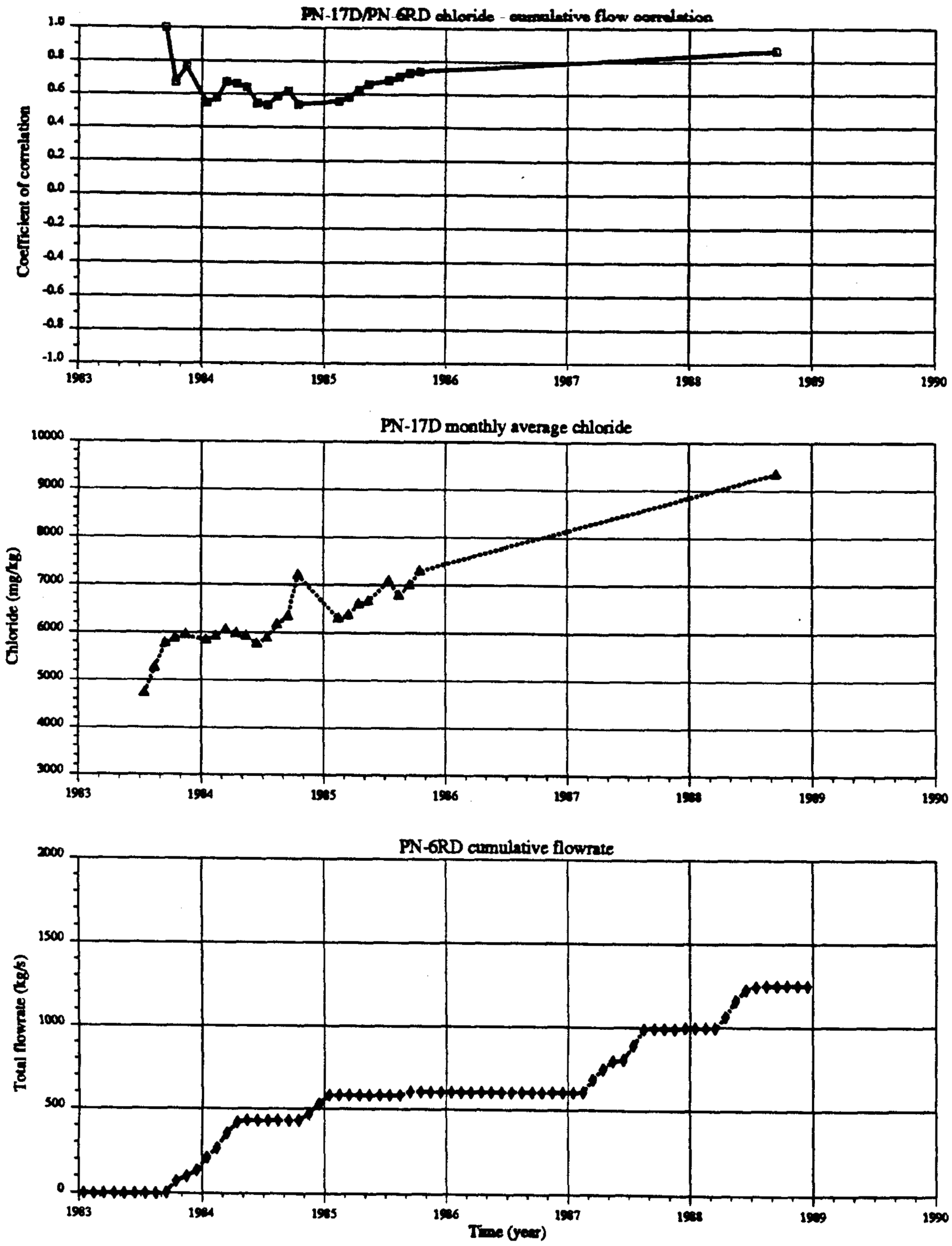


Figure 5.23: Chloride-cumulative flow correlation method on PN-17D/PN-6RD.

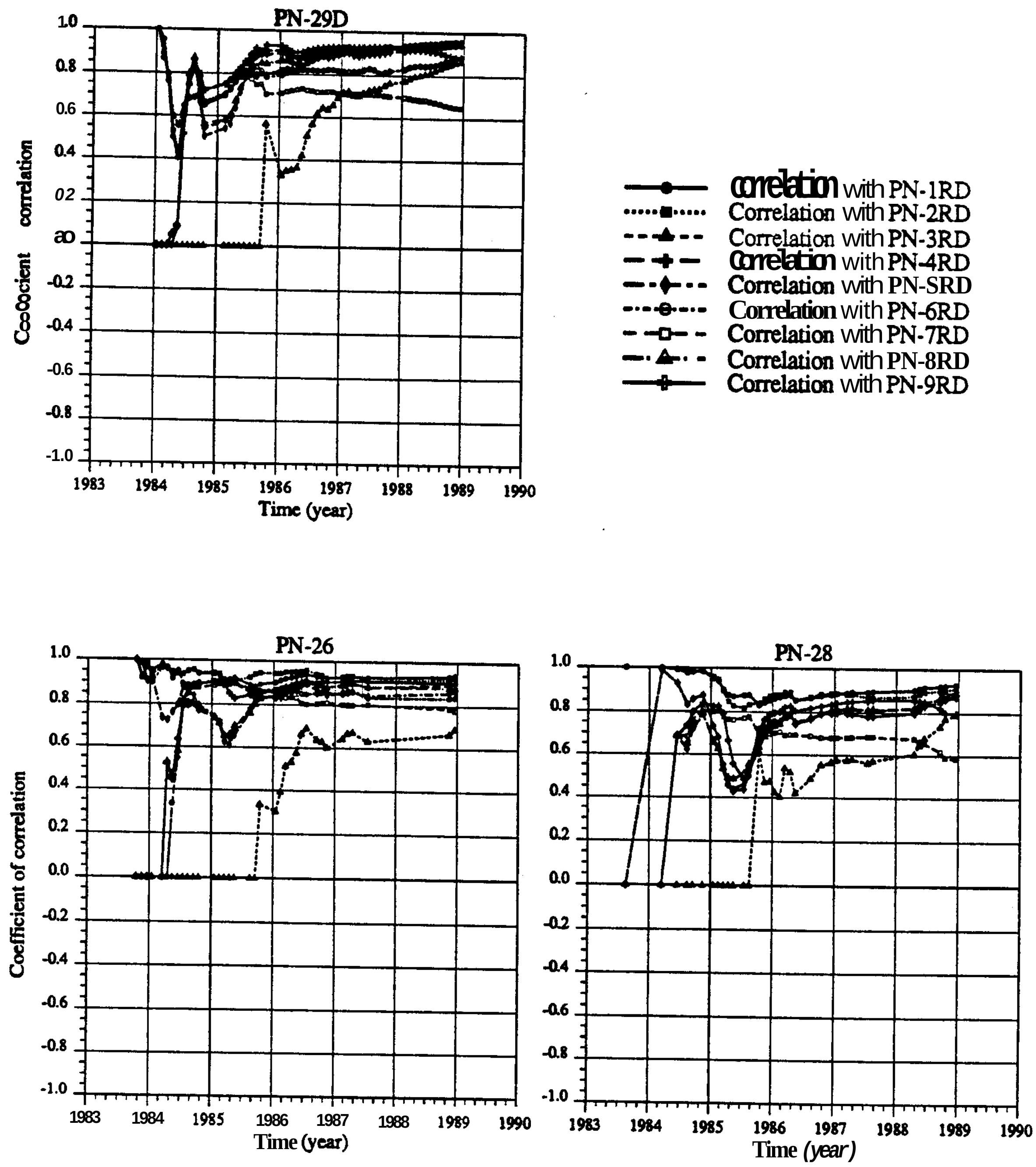


Figure 5.24: Selected chloride-cumulative flow correlations.

producing well. To measure this change, it was assumed that the trend of increasing chloride values can be represented by a linearly regressed line. The magnitude of the change is measured by the deviation of the chloride value from this best fit line and this chloride deviation was, then, correlated with the injection flowrate. Appendix J lists the program for calculating the coefficient of correlation after finding the chloride deviation from the best fit line using linear regression.

Figure 5.25 shows an example of the measured chloride values and the computed best fit line. Figure 5.25 shows successively, the injection flowrates of PN-9RD, the calculated chloride deviation from the linearly regressed line, and the resulting correlation values. It is interesting to note that the chloride deviation values from the best fit line are greatest and coincident with the injection of PN-9RD. Because of this, the correlation values are high and increasing during these periods of excellent accord between the injection flowrates and the chloride changes.

The correlations for the rest of the PN-9RD production wells were calculated using this method and the results are plotted in Figure 5.27. It can be seen that the general shapes of the correlation plots using the two methods are generally similar. However, upon closer examination it appears that the chloride-flow correlation values simulate better the results of the tracer test. As an example, the chloride-flow correlation method shows only OK-1OD to be negatively correlated for the second wave of PN-9RD injection. This is consistent with the results of the PN-9RDtracer test. On the other hand, the chloride deviation-flowrate method registers OK-10D, PN-17D, PN-28, and PN-18D to be negatively correlated with PN-9RD in contrast to the tracer results.

Figure 5.28 shows the result of the chloride deviation- flowrate method on PN-17D and PN-6RD and Figure 5.29 shows the correlation plots of the two methods. **As** in the PN-9RD, the results indicate the chloride-flow correlation to be more reflective of the PN-6RD relationship with these producing wells. To illustrate, the plots of OK-7 and PN-28 are sensitive to the use of PN-6RD for the

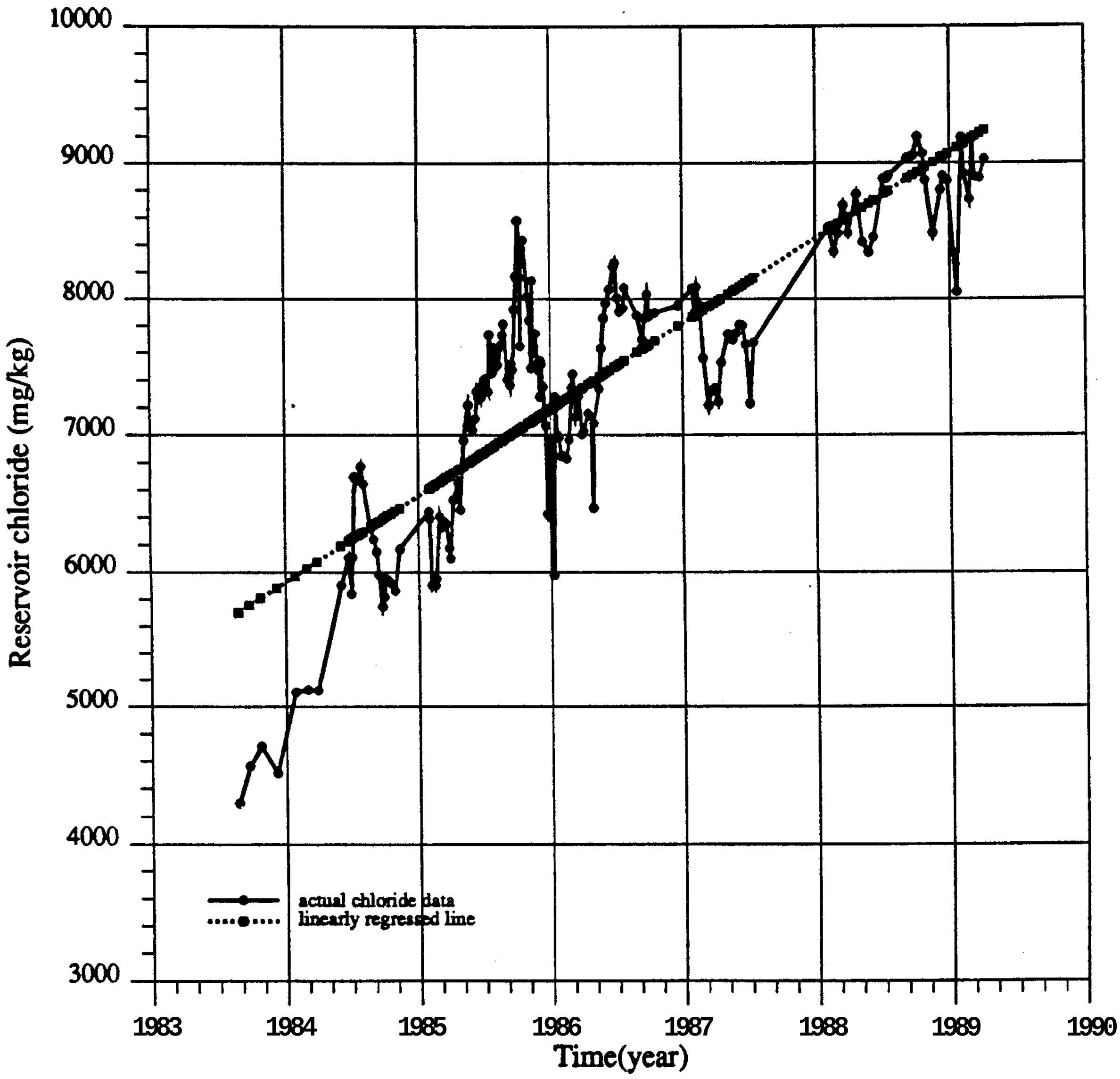


Figure ***5.25:*** Chloride and deviation of chloride from best fit line.

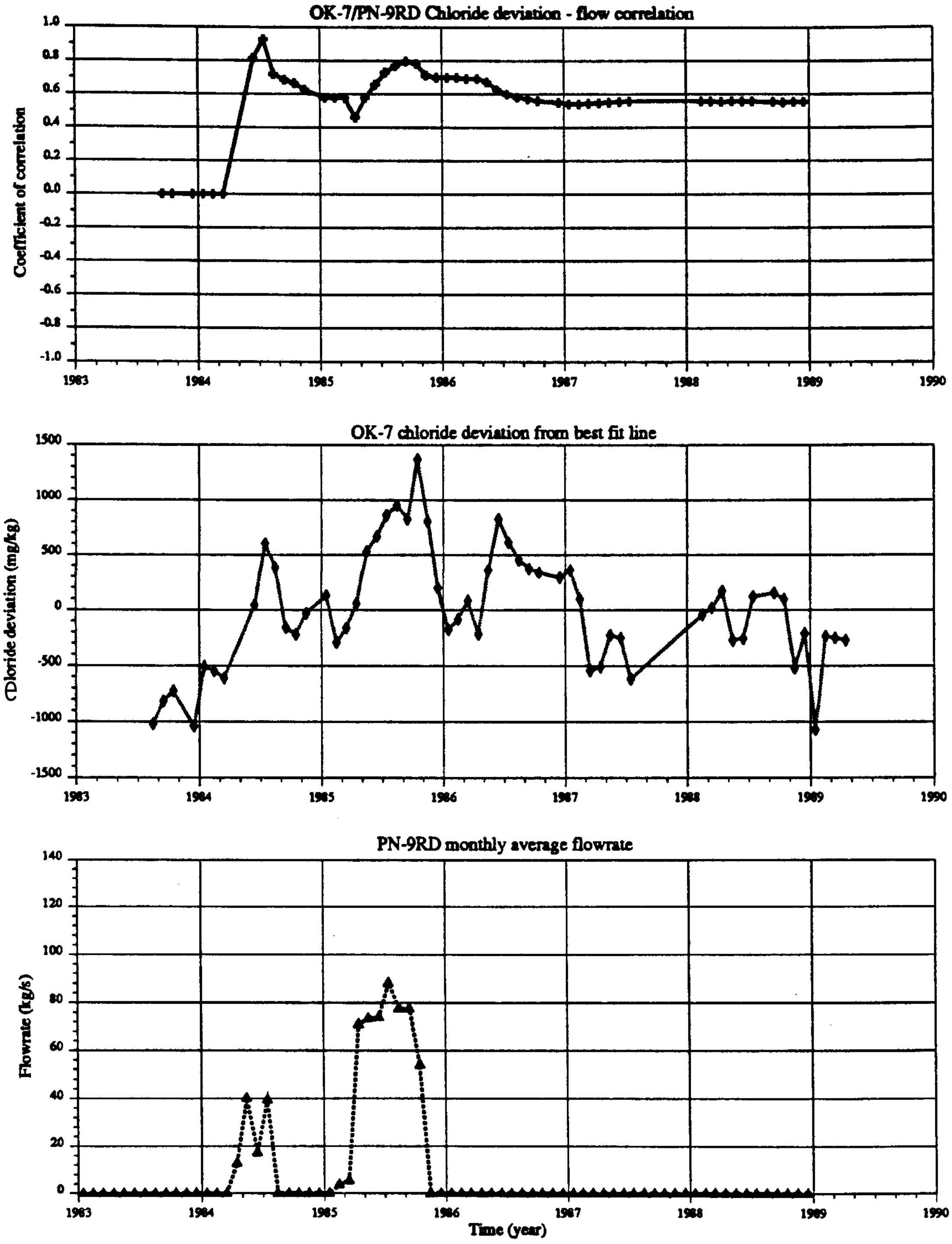


Figure 5.26: Chloride deviation-flow correlation method on OK-7/PN-9RD.

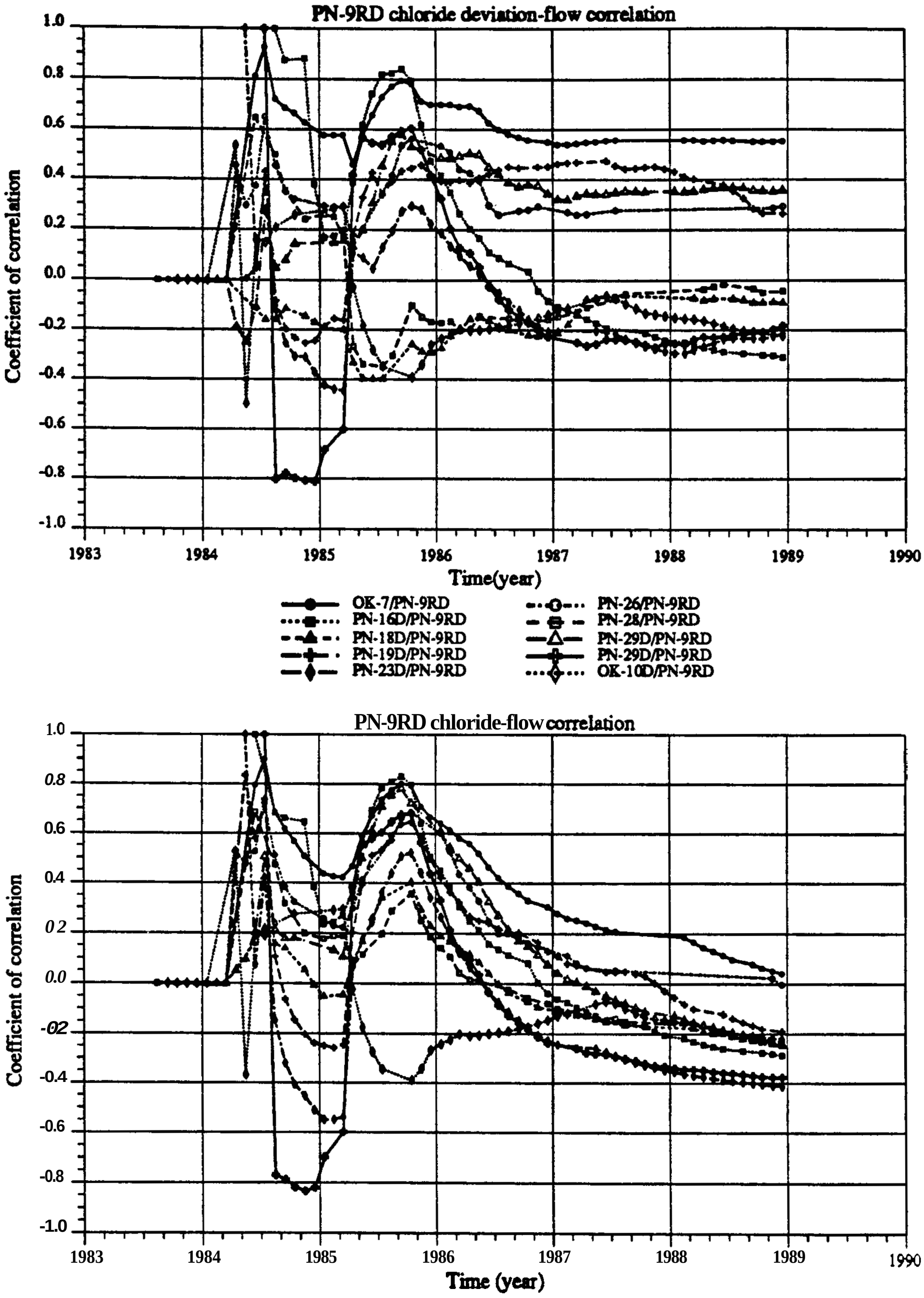


Figure 5.27: PN-9RD tracer test: comparing two chloride-flow methods.

chloride-flow correlation but behave otherwise in the chloride deviation-flowrate correlation. Appendix I shows the plots for the rest of the injection wells using the two correlation methods. The same features are exhibited by these plots as has been discussed for the PN-9RD and the PN-6RD cases.

Therefore, it can be concluded that the chloride-flow correlation method is a better indicator of the strength of the producer/injector relationship.

5.4 Linear Combination Method

The preceding sections have discussed the results of getting the correlation by using the chloride values of a production well and the flowrates of a particular injection well. Of the three methods, the chloride-flow correlation method shows merit in ranking the production wells for a certain injection well. It is, however, limited in its capability to rank the injection wells for a production well since it fails to distinguish the individual contributions from the injection wells.

To take into account the reality that the net effect on a production well is due to the effects of the particular injection wells which were active during the time, the last method expresses the chloride value of the producing well as a linear combination of the injection flowrates of the all the active reinjection wells at the particular time considered. In mathematical symbols, this can be written:

$$\begin{aligned} cl_1 &= a_o + a_1 q_{11} + a_2 q_{21} + a_3 q_{31} + \cdots + a_n q_{n1} \\ cl_2 &= a_o + a_1 q_{12} + a_2 q_{22} + a_3 q_{32} + \cdots + a_n q_{n2} \\ &\vdots \\ cl_i &= a_o + a_1 q_{1i} + a_2 q_{2i} + a_3 q_{3i} + \cdots + a_n q_{ni} \end{aligned} \quad (5.2)$$

where n = number of reinjection wells chosen

i = number of particular time set considered

cl_i = chloride value of well at time i

q_{ni} = injection flowrate of well n at time i

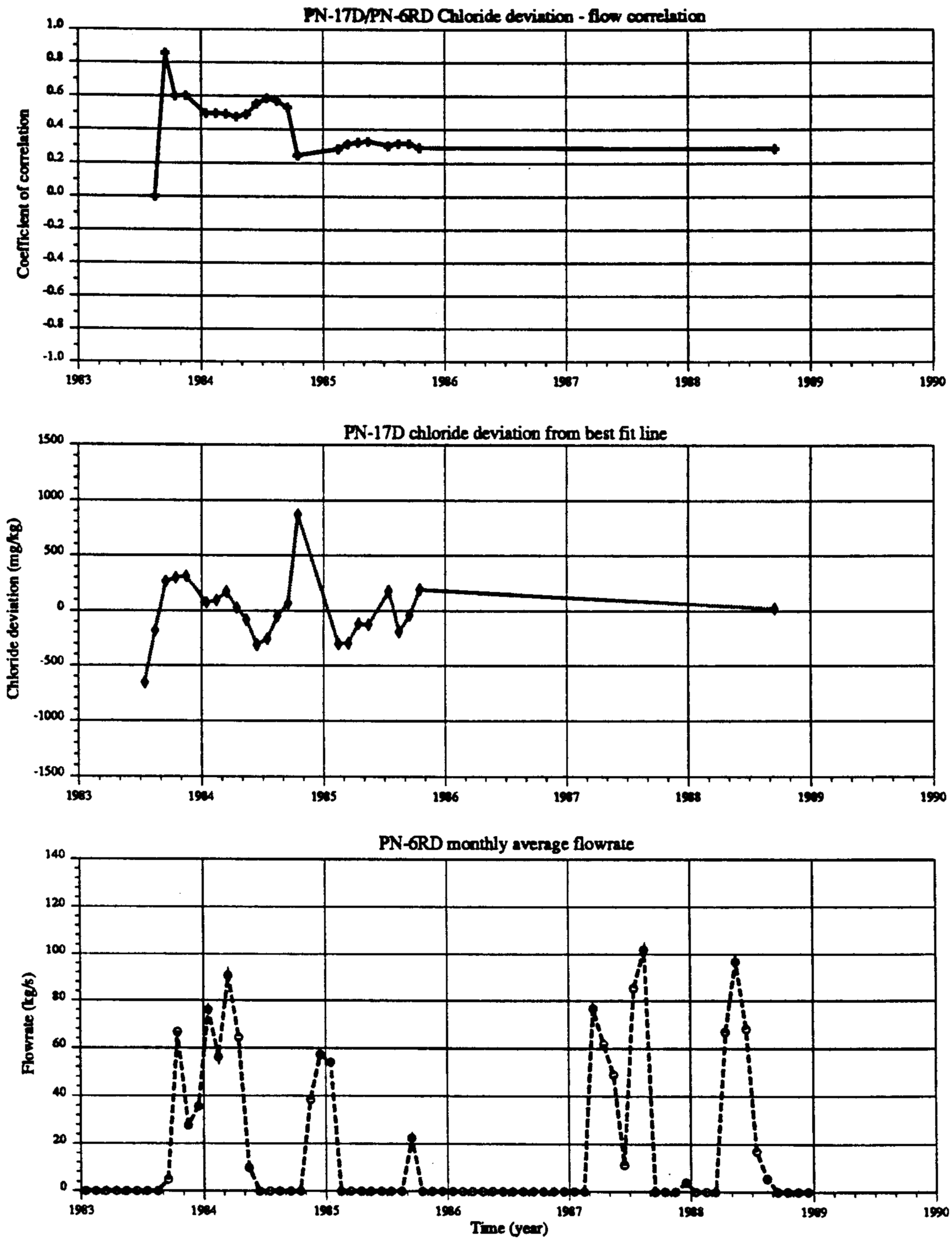


Figure 5.28: Chloride deviation-flow correlation method on PN-17D/PN-6RD.

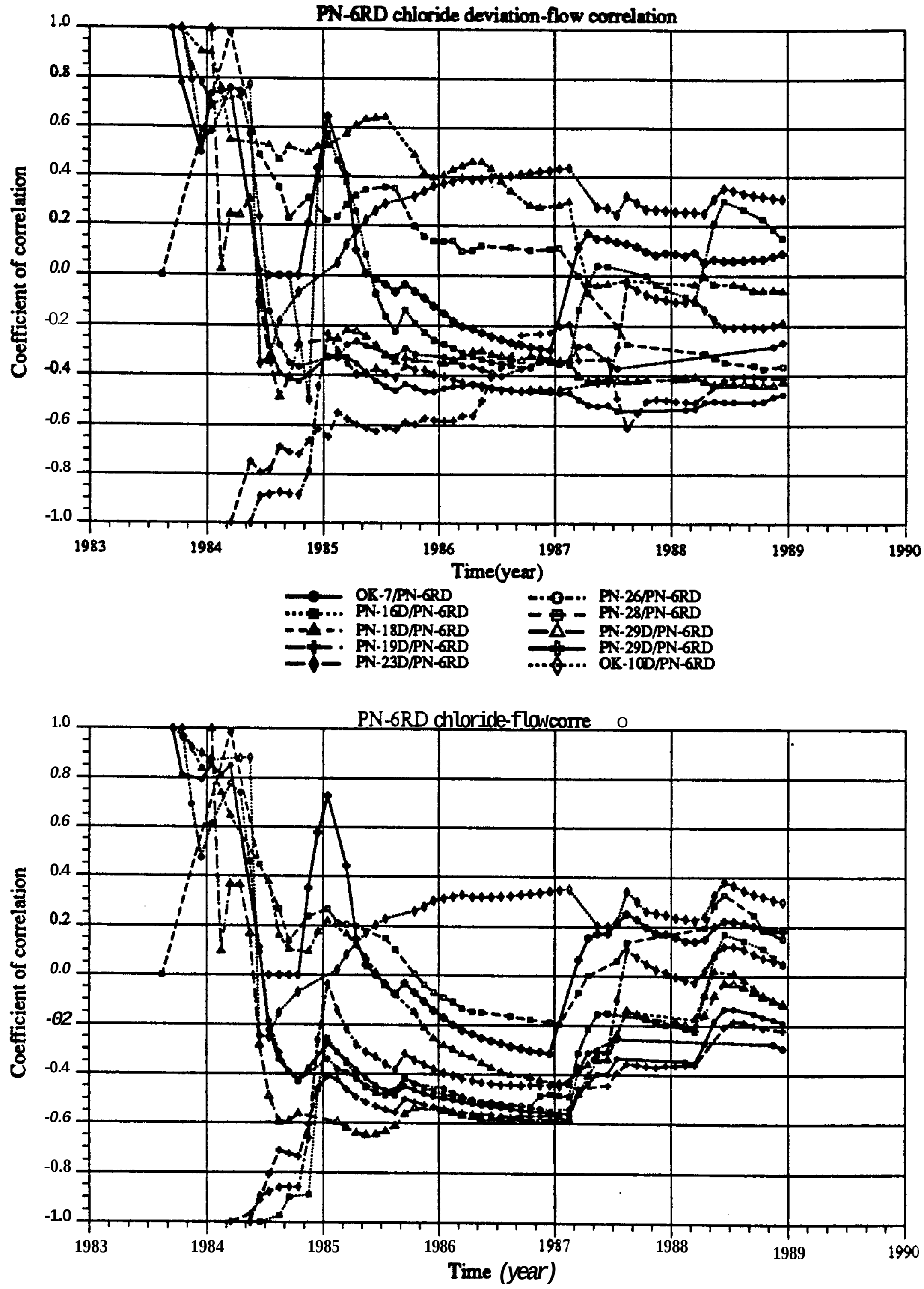


Figure 5.29: OK-12RD/PN-6RD tracer test: comparing two chloride-flow methods.

In a more compact form, this can be written as

$$cl_p = a_o + \sum_{r=1}^{n} a_r q_r \tag{5.3}$$

where cl_p = production chloride value of well p at time t

$a,$ = chloride constant

$a,$ = coefficient of correlation between producer p and injector r

q_r = flowrate of injection well r

As can be seen from Equation **5.3,** with this method, the contribution of each reinjection well to the total chloride value of the producer is considered. If the coefficient relating injection well i to producer p is large, then this implies that more injection fluid returns are coming from well i to well p than another injection well whose coefficient is smaller.

The system of equations corresponding to the selected times for a particular production well as indicated by Equation **5.3** can be put in matrix form **as:**

$$A\vec{x} = \vec{b} \tag{5.4}$$

where the matrix **A,** the solution vector $\vec{x}$, and the right hand side $\vec{b}$ of Equation **5.4** are:

$$A = \begin{vmatrix} \sum_{i=1}^{p} i & \sum_{i=1}^{p} r_{1,i} & \sum_{i=1}^{p} r_{2,i} & \cdots & \sum_{1=i}^{p} r_{n,i} \\ \sum_{i=1}^{p} r_{1,i} & \sum_{i=1}^{p} {r_{1,i}}^2 & \sum_{i=1}^{p} r_{1,i} r_{2,i} & \cdots & \sum_{1=i}^{p} r_{1,i} r_{n,i} \\ \sum_{i=1}^{p} r_{2,i} & \sum_{i=1}^{p} r_{1,i} r_{2,1} & \sum_{i=1}^{p} {r_{2,i}}^2 & \cdots & \sum_{1=i}^{p} r_{2,i} r_{n,i} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \sum_{i=1}^{p} r_{n,i} & \sum_{i=1}^{p} r_{1,i} r_{n,1} & \sum_{i=1}^{p} r_{2,i} r_{n,i} & \cdots & \sum_{1=i}^{p} {r_{n,i}}^2 \end{vmatrix} \tag{5.5}$$

$$\vec{x} = \begin{vmatrix} a_o \\ a_1 \\ a_2 \\ \vdots \\ a_n \end{vmatrix} \qquad \vec{b} = \begin{vmatrix} \sum_{i=1}^{n} cl_i \\ \sum_{i=1}^{n} r_{1,i} cl_i \\ \sum_{i=1}^{n} r_{2,i} cl_i \\ \vdots \\ \sum_{i=1}^{n} r_{n,i} cl_i \end{vmatrix} \tag{5.6}$$

The solution to these simultaneous linear equations is solved by a matrix solver which used the Gauss-Jordan method. It has been modified so that the constant ***a,*** takes on the chloride value at the initial time defined. Sometimes, it may happen that the matrix ***A*** is singular which means no solution exists to the system of equations. In this instance, the program prints a "no solution" message. Appendix K gives the source program listing and an example of an output which gives the coefficients for the time interval and injection wells specified by the user.

5.4.1 Results Using Whole Data Set

As the title suggests, the coefficients of correlation were calculated for the **Pal**inpinon production wells using all the injection wells from August **1983** to December **1988.** The results are given by Table **5.5.**

Table **5.5** has been put in horizontal stacked bar forms (Figures **5.30** and **5.31)** in order to see more clearly the contributions of each reinjection well to a **pro**duction well (row analysis) and the production wells affected in varying degrees by each injection well (columnar analysis). Each bar corresponds to a row of coefficient values which are horizontally stacked to make up the total bar. These bars represent only wells with positive correlations, and therefore, the absentee wells are those of negative correlation with either the production or reinjection well, as the case may be.

From Figures **5.30** and **5.31,** the following aspects have been observed and determined:

- The different contributions of the reinjection wells to a particular production wells are now separated and made distinguished. As an example. it can been from the stacked bar of **PN-29D** that this well is strongly influenced by PN-9RD, followed by PN-3RD, PN-8RD, PN-1RD, PN-4RD, and PN-6RD. The rest of the injection wells do not correlate positively with **PN-29D.**

Table ***5.5*** **Linear** combination coefficients **for whole** data **set.**

Production Well	PN-1RD	PN-2RD	PN-3RD	PN-4RD	PN-5RD	PN-6RD	PN-7RD	PN-8RD	PN-9RD
OK-1OD	4.04	-11.51	1.74	2.87	**-7.66**	4.19	**5.30**	2.65	1.83
OK-7	11.93	-21.92	28.56	5.00	11.21	8.15	-6.83	20.94	29.38
OK-9D	4.75	-20.93	19.70	8.14	-21.16	3.19	-16.47	4.79	16.34
PN-14	10.95	-37.61	32.04	42.54	-25.44			32.56	-
PN-15D	12.98	-19.02	37.14	-1.53	-6.59	5.39	**-0.30**	11.06	0.22
PN-16D	3.84	-15.95	17.46	0.47	-7.90	3.60	-12.05	13.03	16.04
PN-17D	13.58	-9.16		3.64	32.22	7.72	2.67	-2.84	3.06
PN-18D	10.84	-19.98	25.06	-3.74	11.78	12.27	-13.05	24.98	23.06
PN-19D	6.18	-16.27	16.64	3.22	-5.27	0.77	-20.89	16.37	17.85
PN-21D	12.90	-24.98	31.25	-219 1	5.03	13.94		13.59	-
PN-23D	6.90	-16.36	26.10	9.68	-9.45	4.49	17.71	8.94	17.46
PN-24D	9.35	-37.37	21.18	-32.87	24.33	10.42	-21.75	18.65	37.73
PN-26	9.41	-14.72	2522	5.45	5.50	7.60	-6.21	14.80	20.52
PN-27D	12.87	-19.80	31.78	15.59	-19.98	8.10	-21.50	**10.56**	35.15
PN-28	9.72	-9.00	22.61	**-4.60**	15.13	8.75	-1.42	21.30	17.09
PN-29D	14.95	-39.60	46.48	18.79	-25.15	9.30	-36.86	22.16	43.34
PN-30D	2.48	-5.05	12.49	3.35	-5.16	2.73	-8.68	1.32	6.20
PN-31D	8.85	-17.22	28.21	3.00	-16.62	5.31	-28.94	17.86	31.31

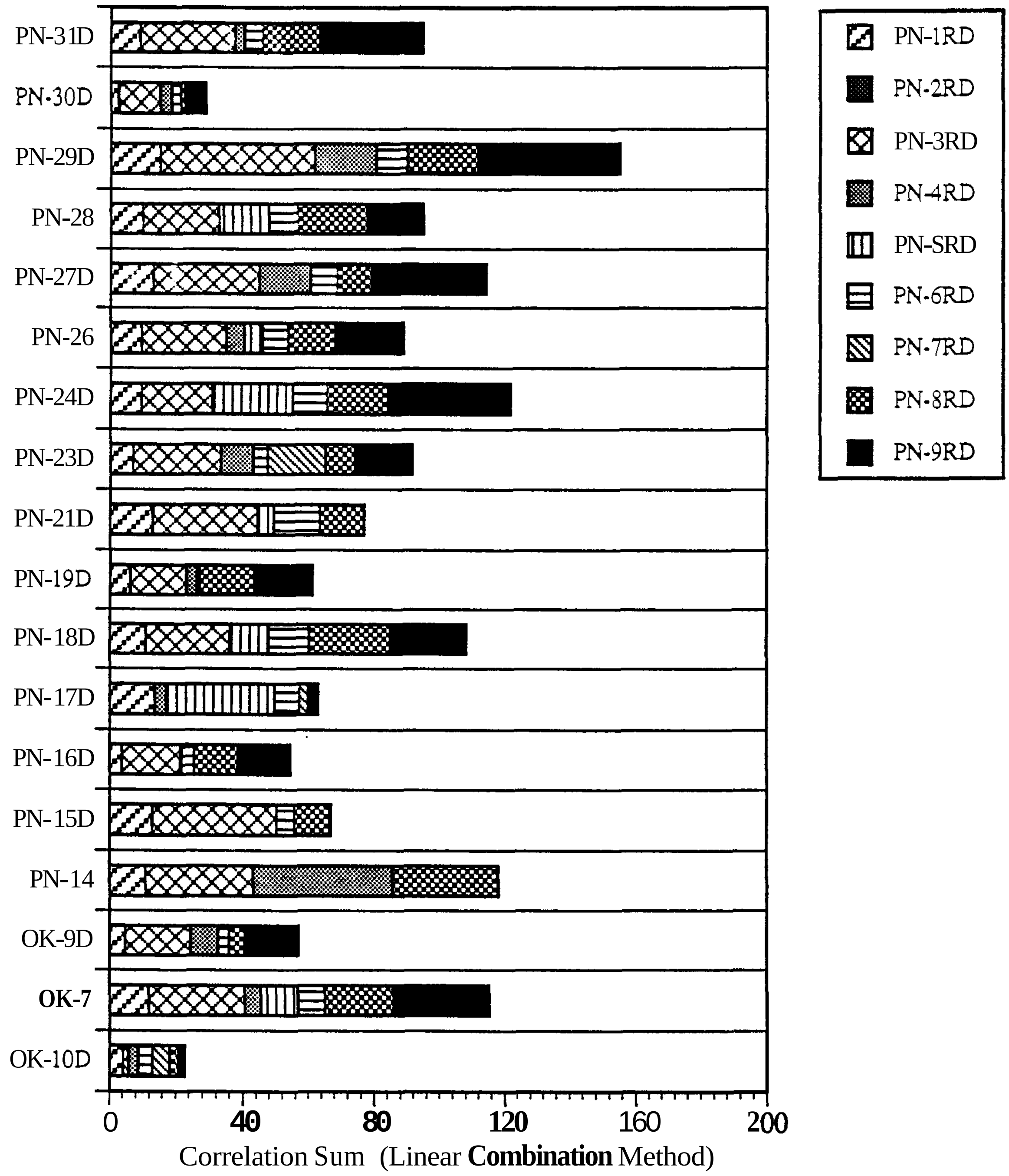


Figure **5.30:** Linear combination coefficients featuring production wells.

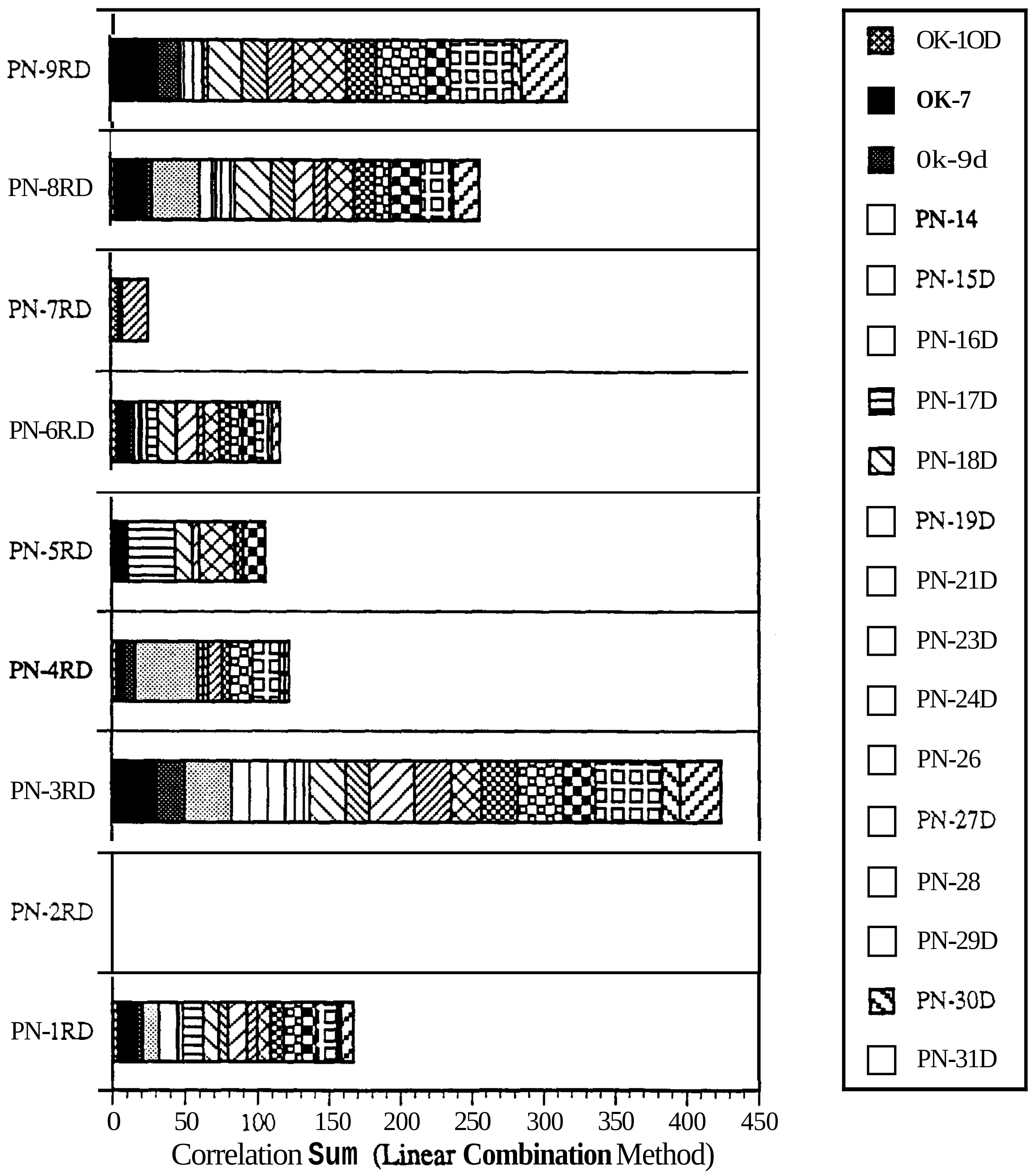


Figure **5.31:** Linear combination coefficients featuring injection wells.

- Since the coefficient sum is taken to be indicative of the extent of reinjection returns to a producing well, then the most affected by these returns is well PN-29D. It is followed by the group of wells PN-24D, PN-14, OK-7, PN-27D, and PN-18D. Next is the group composed of PN-28, PN-31D, PN-23D, and PN-26. Least affected are PN-16D, OK-9D, PN-SOD and, finally, OK-10D.

  This ranking is similar to but not exact to that given in Section 3. It similarly identifies PN-29D as the well which has produced the most injection fluid returns followed by wells PN-26, PN-28, OK-7, PN-19D. Affected to a lesser degree are the wells PN-23D, PN-18D, PN-31D, PN-15D, and PN-30D. While this ranking is based on cumulative mass of reinjection fluids discharged by the wells, the previous ranking is based on a rate of being affected by injection returns since the coefficients a_i take on the units of chloride per injection flowrate. The linear combination method, therefore, identifies PN-24D and PN-27D as two other wells with strong interaction to the production wells. The relative magnitudes are given by the coefficients of correlation.

- From the relative widths of the individual bars, it can be inferred that most production wells are affected by PN-9RD and PN-3RD. This is made more evident in Figure 5.31 where PN-2RD draws a blank implying that it has no correlation with any of the production wells at all. A glance at Figure 5.31 would rank the injection wells on the basis of their potential to communicate with the producing sector in the following order: PN-3RD, PN-9RD, PN-8RD, PN-1RD, PN-6RD, PN-4RD, PN-5RD, PN-7RD, and PN-2RD. Under this context, Section 3 identifies PN-2RD, PN-3RD, PN-4RD and PN-5RD as wells with no or minimal communication with the producing blocks. Hence, while the results agree for PN-4RD, PN-5RD and PN-2RD, there is a big disparity with reinjection well PN-3RD. The linear combination method indicates PN-3RD to communicate strongly with the producers. It is also believed that the PN-7RD correlation may not be accurate due to the fact that it was on-line only for the very brief period of May-July 1984 and consequently, contributed only three data points for the whole time considered.

At this junction, it would be interesting to compare the results of the linear combination method with the chloride-flow method for the tracer tests, in particular, and as a whole in general.

Table 5.6 shows how the monitored production wells were ranked according to the tracer tests, the chloride-flow correlation method and the linear combination method. There are differences in the three columns on the ranking of the wells. While the chloride-flow method ranks OK-7 first in agreement with the tracer result, the linear combination method ranks PN-29D first. In terms of relative ranking of the production wells, the chloride-flow method is closer to the tracer data. For the OK-12RD/PN-6RD, the production wells affected are in agreement but the relative ranking is not.

Since it has been stated that one deficiency of the chloride-flow method is the inability to distinguish the different contributions of the reinjection wells to a particular production well, comparison will be made between the reinjection wells and the production wells communicated with. Table 5.7 is a coalescence of Table 5.4 of the chloride-flow correlation method and Table 5.5 of linear combination method. Figure 5.32 shows the results of the chloride-flow correlation method drawn from Table 5.7.

When Figure 5.32 is compared to Figure 5.31, the following similarities and differences are noted:

- Both figures have injection well PN-2RD as communicating least with the producers. But while the linear combination method has negative correlations for PN-2RD, the chloride-flow method has positive, although low correlations, of PN-2RD with PN-26, PN-24D, PN-SOD, PN-31D, and PN-19D.
- The linear combination has ranked PN-3RD, PN-9RD, PN-8RD, and PN-1RD as the first four most "harmful" wells. The chloride-flow method has

Table 5.6: **Comparing** tracer tests **and** the correlation **methods.**

PN-9RD Tracer Test Ranking	**Chloride-Flow Correlation**	Linear Combination Coefficient
OK-7	OK-7	PN-29D
PN-26	PN-16D	PN-31D
PN-28	PN-26	OK-7
PN-29D	PN-28	PN-18D
PN-18D	PN-18D	PN-26
PN-23D	PN-17D	PN-28
PN-16D	PN-23D	PN-16D
PN-19D	OK-1OD	PN-30D

OK-12RD/PN-6RD Tracer Test **Ranking**	**Chloride-Flow** Correlation	Linear Combination Coefficient
PN-17D	PN-28	PN-21D
OK-1OD	OK-10D	PN-29D
OK-7	OK-7	PN-28
PN-28	PN-26	OK-7
PN-15D	PN-17D	PN-17D
PN-26	PN-15D	PN-26
PN-21D	PN-21D	PN-15D
		OK-10D

Table 5.7: Representative coefficients from the two correlation methods.

PRODUCTION WELL	METHOD	PN-1RD	PN-2RD	PN-3RD	PN-4RD	PN-5RD	PN-6RD	PN-7RD	PN-8RD	PN-9RD
		REINJECTION WELLS								
OK-10D	Q-Flow Corr	0.38	-0.28	-0.15	-0.38	-0.59	033	0.42	0.17	-0.39
	Lin Comb Coeff	4.04	-11.51	1.74	2.87	-7.66	4.19	5.30	2.65	1.83
OK-7	Q-Flow Corr	-0.12	-0.17	0.66	0.90	0.81	-0.18	0.91	0.48	*0.80*
	Lin Comb *Coeff*	11.93	-21.92	28.56	5.00	11.21	8.15	-6.83	20.94	29.38
OK-9D	Q-Flow Corr	-0.36	-0.55	0.66	052	0.28	0.43	0.29	0.10	0.14
	Lin Comb Coeff	4.75	-20.93	19.70	8.14	-21.16	3.19	-16.47	4.79	16.34
PN-14	Q-Flow Corr	-0.16	-0.89	0.77	0.70	0.68	-0.12		0.96	-
	Lin Comb Coeff	10.95	-37.61	32.04	42.54	-25.44			3256	-
PN-15D	Q-Flow Corr	0.19	-0.14	0.95	059	0.81	0.17	0.26	0.58	0.30
	Lin Comb Coeff	1298	-19.02	37.14	-1.53	-6.59	5.39	-0.30	11.06	0.22
PN-16D	Q-Flow Corr	-0.16	0.08	0.72	0.77	0.49	0.17		0.46	0.83
	Lin Comb Coeff	3.84	-15.95	17.46	0.47	-7.90	3.60	-12.05	13.03	16.04
PN-17D	Q-Flow Corr	0.18	0.06		0.50	0.71		0.16		0.61
	Lin Comb Coeff	13.58	-9.16		3.64	32.22	7.72	2.67	-2.84	3.06
PN-18D	Q-Flow Corr	-0.41	-0.36	0.74	0.59	0.60	0.02	0.23	0.52	0.40
	Lin Comb Coeff	10.84	-19.98	25.06	-3.74	11.78	12.27	-13.05	24.98	23.06
PN-19D	Q-Flow Corr	0.11	0.15	0.64	0.88	0.79	-0.18	0.97	0.54	0.65
	Lin Comb Coeff	6.18	-16.27	16.64	3.22	-5.27	0.77	-20.89	16.37	17.85
PN-21D	Q-Flow Corr	-0.06	-0.65	0.83	0.82	0.81	0.35		*0.80*	-
	Lin Comb Coeff	1290	-24.98	31.25	-21.91	5.03	13.94		13.59	-
PN-23D	Q-Flow Corr	-0.34	0.10	0.83	0.87	0.61	0.12	0.93	0.23	0.52
	Lin Comb Coeff	6.90	-16.36	26.10	9.68	-9.45	4.49	17.71	8.94	17.46
PN-24D	Q-Flow Corr		0.25	0.77	0.72	0.79	0.15	0.56	0.60	0.86
	Lin Comb Coeff	9.35	-37.37	21.18	-3287	24.33	10.42	-21.75	18.65	37.73
PN-26	Q-Flow Corr	0.12	0.31	0.76	0.79	*0.80*	-0.25	0.80	0.37	0.69
	Lin Comb Coeff	9.41	-14.72	25.22	5.45	550	7.60	4.21	14.80	20.52
PN-27D	Q-Flow Corr	-0.01	-0.19	0.78	0.88	0.81	-0.20	0.81	0.47	0.72
	Lin Comb Coeff	1287	-19.80	31.78	15.59	-19.98	8.10	-21.50	10.56	35.15
PN-28	Q-Flow Corr	0.19	-0.33	0.70	0.54	053	0.29	0.75	0.27	*0.36*
	Lin Comb Coeff	9.72	-9.00	22.61	-4.60	15.13	8.75	-1.42	21.30	17.09
PN-29D	Q-Flow Corr	0.22	*0.07*	0.76	0.90	0.72	-0.03	0.08	0.43	0.78
	Lin Comb Coeff	14.95	-39.60	46.48	18.79	-25.15	9.30	-36.86	22.16	43.34
PN-30D	Q-Flow Corr		0.27	0.82	0.73	0.51	0.22		-0.11	0.68
	Lin Comb Coeff	248	-5.05	1249	3.35	-5.16	273	-8.68	1.32	6.20
PN-31D	Q-Flow Corr	0.75	0.17	0.65	0.87	0.71	0.07	0.96	0.39	0.80
	Lin Comb Coeff	8.85	-17.22	28.21	3.00	-16.62	5.31	-28.94	17.86	31.31

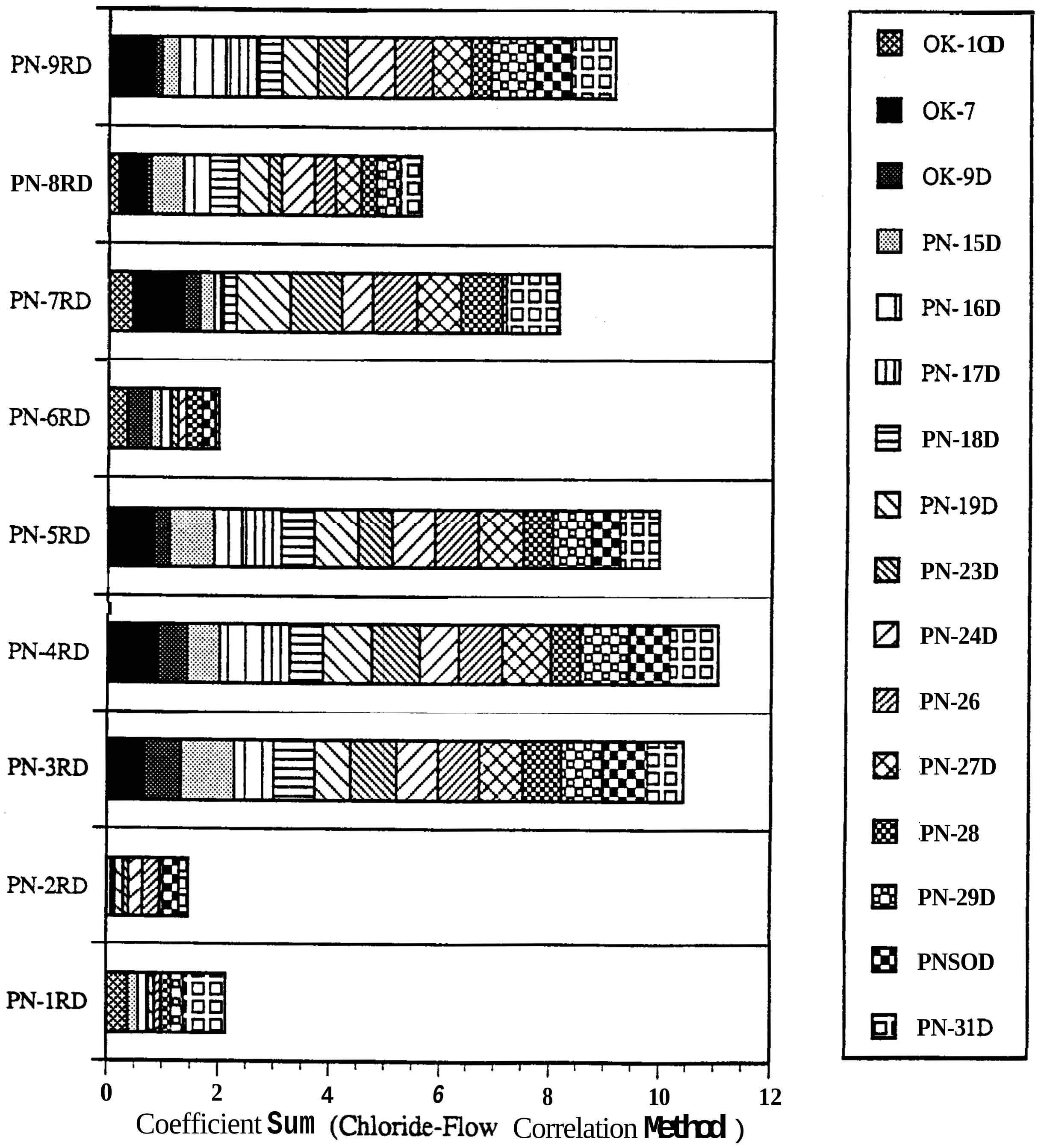


Figure **5.32:** Chloride-flow correlations featuring reinjection wells.

them as PN-4RD, PN-3RD, PN-5RD, and PN-8RD, while the last in the hierarchy to do damage are PN-GRD, PN-1RD, and PN-2RD. From previous discussions on chloride-flow correlation method, it was put forward that the reason for the high correlation coefficients of PN-3RD, PN-4RD, PN-5RD, PN-8RD was the continuous utilization of these wells during the time interval. The results of the linear combination method, on the other hand, do not show such dependence on the injection well utilization since PN-4RD, PN-5RD, and PN-6RD have much lower correlations compared to PN-3RD. It will be reiterated that the wells ranked with no or minimal communication to the producing sectors are PN-2RD, PN-3RD, PN-4RD, and PN-5RD and the wells proven "deleterious" are PN-9RD, PN-8RD, PN-7RD, PN-1RD, and PN-6RD. Therefore, it can be seen that the linear combination method approaches that of the field experience results.

To conclude, this section shows that the linear combination method is more sensitive to the producer/injector relationship. Therefore, the coefficients of correlation between injector/producer pairs can be used as inputs in the algorithms to optimize the production and injection strategy of the geothermal field under exploitation.

5.4.2 Using the Linear Combination Method in More Detail

The linear combination method may be used to investigate in more detail the relationships of the injection wells with the producers. By using appropriate time intervals where different sets of injection wells are used, the method can be used to define more clearly the contributions of the injection wells to the producing well.

As an example, Table 5.8 shows some runs on OK-7 for different time intervals with different reinjection wells being active during these times. Run No. 1 uses the whole data set for all wells. The result shows PN-9RD and PN-3RD with

Table 5.8: Example of linear combination use.

PROD WELL	Run	TIME INTERVAL	PN-1RD	PN-2RD	PN-3RD	PN-4RD	PN-SRD	PN-6RD	PN-7RD	PN-8RD	PN-9RD
OK-7	1	Aug 83 - Dec 89	11.93	-21.92	2856	5.00	11.21	8.15	-6.83	20.94	29.38
	2	Nov 85 - Jul 88	4.54	-59.93	1208	-11.26	1054	1.23	-	13.25	-
	3	Oct 85 - Jul 88	3.45	-43.81	6.24	-2235	13.65	269	-	1138	-
	4	Aug 83 - Aug 85	5.37	-5.95	-	7.16	-8.54	7.79	-13.46	25.42	35.10
	5	Aug 83 - Aug 85	5.81	-6.96	-	2.05	9.82	1.23	-	20.97	27.23
	6	Jun 84 - Aug 85	1.04	6.20	-	-8.97	13.72	-		7.79	16.60

the highest comparable coefficients, followed by PN-8RD, PN-1RD, PN-5RD, PN-GRD, and PN-4RD. The remaining wells, PN-2RD and PN-7RD were not correlated positively. Since this run showed a small difference between PN-3RD and PN-9RD, additional runs were made to resolve which of the two contributes more to OK-7.

In Runs No. 2 and 3, representing smaller time intervals than Run 1, PN-7RD and PN-9RD were not in service. In both instances, except in PN-5RD, correlations decrease to much lower values which seems to indicate that this is an effect of removing PN-9RD. Similarly, PN-8RD had higher correlation to OK-7 than PN-3RD.

In Run No. 4, PN-3RD was disconnected from service. The result indicated PN-9RD and PN-8RD to have very high correlations, implying that during this time interval, the chloride increases of OK-7 can be virtually attributed to these two wells. To a smaller extent, following PN-8RD are wells PN-GRD, PN-4RD, and PN-1RD. It is interesting to see the effect of taking out the contribution of PN-7RD. Run No. 5 is similar to Run No. 4 except that PN-7RD was assumed to be out of service the whole time interval since, in fact, PN-7RD was used only for a very short period of time. The result showed a slight decrease in the high correlations of PN-9RD and PN-8RD, although these two wells maintained their previous ranking in Run No. 4. The only other well which was affected by this hypothetical run was PN-5RD whose correlation switched from a negative to a positive value.

For the last run (Run No. 6), wells PN-3RD, PN-6RD and PN-7RD were not employed. Again, the results showed highest coefficients for PN-9RD, followed by PN-5RD and PN-8RD.

In summary, while the whole data set tends to purport that PN-3RD and PN-9RD as almost equal in contribution to producer OK-7, the subsets or actual runs for different time intervals prove that PN-9RD actually has a much greater weight. It also shows that PN-8RD comes in second, followed by PN-3RD, PN-5RD, PN-6RD, and PN-1RD.

This illustrates simply how the linear combination method can be used to investigate, by the process of deduction, the different roles played by the reinjection wells to the producing wells. In this manner, it can serve as another tool for the efficient management of the reservoir by identifying "fast" reinjection paths.

Section 6

Conclusions and Recommendation

1. The Palinpinon-I tracer tests results, along with field geometry and well/field operating constraints were successfully used as input to the algorithms developed and modified by James Lovekin to allocate production and reinjection rates to the Palinpinon-I wells. The algorithms employing linear and quadratic programming allocated the same rates to the wells and curtailed the wells one by one partially, then completely, depending on the propensity for thermal breakthrough as indicated by the producer/injector cost coefficient.

2. Due to economic and operational constraints imposed by tracer tests, there was a need to look for another parameter that can replace tracer data coefficients in the optimization algorithms. The chloride value was used because it was good indicator of the magnitude and strength of the relationship between the injector and the producer. Four different methods were employed to obtain the correlation between a producer and an injector.

3. One method obtained the correlation between the chloride value and the cumulative flowrate of the injection well. The method, however, had to be

disregarded because it tended to give positive high coefficients throughout the time interval and did not differentiate sufficiently correlation among the reinjection wells.

4. Another method obtained the correlation between the deviation of chloride from the best fit line to the chloride trend and the injection flowrate of the well. This method was better than the first but had to be discarded because it produced results contrary to the tracer return data.

5. The third method which determined the correlation between the chloride value and the injection flowrate approaches the tracer test results. It can be used to rank production wells for each reinjection well, but fails to separate or distinguish the contributions of the different injection wells for a particular production well. It also displayed greater sensitivity or dependency on the utilization of the injection well.

6. This deficiency is overcome by the linear combination method which expresses the chloride value as a linear combination of the injection wells active during the time interval considered. As such, the weights of the injection wells are taken into account. The result showed that the ranking of the reinjection wells according to the propensity for communication with the producing sector is very close to that determined from field observation. It is, however, different in ranking PN-3RD first.

7. The linear combination method can also rank production wells affected by reinjection returns. The results verify that PN-29D is most severely affected and imply that PN-24D, PN-18D, and PN-27D are three other wells greatly affected by reinjection returns.

8. The coefficient of correlation between producer/injector pair calculated from the linear combination method can be used as arc cost coefficients to optimize the well utilization strategy. However, this is useful only when the geothermal field still has the flexibility to utilize and manipulate the appropriate wells.

9. The Palinpinon Geothermal Field has a wealth of production and chemical

data which are usually functions of time. It is recommended that these data undergo analysis for time series modeling and forecasting which may be used for reservoir simulation and field management.

Appendix A

Production and Injection Zones of Paln-I Wells

Table A.l: Production and injection depths.

PRODUCTION WELL	Major Zone	Minor Zones		REINJECTION WELL	Major Zone	Minor Zones	
OK-7	1983.9	868.9		OK-12RD	1280.2	865.2	
OK-9D	1419.8	734.8		PN-1RD	785.1	1220.1	2115.1
OK-10D	643.9	1636.4		PN-2RD	1995.1	740.1	2560.1
PN-13D	708.9	1006.4	1243.9	PN-3RD	2285.2	1685.2	13102
PN-14	2039.5	739.5	1539.5	PN-4RD	2105.0	1393.5	
PN-15D	886.7	1384.2	506.7	PN-SRD	835.1	475.1	1185.1
PN-16D	1388.8	2116.3		PN-6RD	1220.2	420.2	840.2
PN-17D	1289.2	891.7	2234.2	PN-7RD	1889.8	184.8	534.8
PN-18D	1288.9	2048.9	821.4	PN-8RD	1190.0	332.5	570.0
PN-19D	2014.5	609.5		PN-9RD	2177.5	697.5	1872.5
PN-20D	1078.9	543.9					
PN-21D	1434.2	499.2	956.7				
PN-22D	883.8	1458.8	1863.8				
PN-23D	1330.9	688.4	1780.9				
PN-24D	1234.5	764.5	2129.5				
PN-26	934.0	1234.0	1509.0				
PN-27D	648.8	1298.8	2026.3				
PN-28	784.3	434.3	18593				
PN-29D	827.0	1459.5	1789.5				
PN-30D	1155.9	595.9	2050.9				
PN-31D	339.5	1934.5	1519.5				

All depths are meters vertical referred to mean sea level.
Depths are midpoints of permeable zones taken from
from Palinpinon I well data and interpretation.

Appendix B

Sample Output from Linear Programming

```
***************************
* OUTPUT FOR PROGRAM LPAL3 *
***************************

Number of Injectors = 2
Number of Producers = 21

The following factors were used to weight
   the cost coefficients in the objective function:
( 1) Reciprocal of Time to Peak Tracer Response
( 2) Fractional Tracer Recovery
( 3) Reciprocal of Production Rate During Tracer Tests
( 4) Reciprocal of Injection Rate During Tracer Tests
( 5) Exponential of Downhole Elevation Change
     from Producer to Injector

Fieldwide Production Rate Required = 930.0000000000000
Fieldwide Injection Rate Required = 260.0000000000000

Maximum Allowable Number of Iterations to Achieve
   Convergence = 10

SOLVING FOR INJECTION RATES: ITERATION No. 1

Cost for Arc(OK12RD-OK-7  ) = 5.4696956007021020E-06
Cost for Arc(OK12RD-OK-9D ) = 0.0000000000000000
Cost for Arc(OK12RD-OK-10D) = 7.5496887711195760E-06
Cost for Arc(OK12RD-PN-13D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-14 ) = 0.0000000000000000
Cost for Arc(OK12RD-PN-15D) = 3.2026336236172510E-06
Cost for Arc(OK12RD-PN-16D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-17D) = 3.7071432714437670E-04
Cost for Arc(OK12RD-PN-18D) = 0.0000000000000000
```

```
Cost for Arc(OK12RD-PN-19D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-20 ) = 0.0000000000000000
Cost for Arc(OK12RD-PN-21D) = 1.3991935990562930E-08
Cost for Arc(OK12RD-PN-22D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-23D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-24D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-26 ) = 1.7851251629732990E-08
Cost for Arc(OK12RD-PN-27D) = 0.000000000000000
Cost for Arc(OK12RD-PN-28 ) = 9.0316662914056570E-06
Cost for Arc(OK12RD-PN-29D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-30D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-31D) = 0.0000000000000000
Cost for Arc(PN9RD -OK-7  ) = 2.2025224339548620E-03
Cost for Arc(PN9RD -OK-9D ) = 0.0000000000000000
Cost for Arc(PN9RD -OK-10D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-13D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-14 ) = 0.0000000000000000
Cost for Arc(PN9RD -PN-15D) = 0.000000000000000
Cost for Arc(PN9RD -PN-16D) = 5.5355375404810890E-07
Cost for Arc(PN9RD -PN-17D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-18D) = 5.1577506189748170E-05
Cost for Arc(PN9RD -PN-19D) = 2.3387563710857180E-07
Cost for Arc(PN9RD -PN-20 ) = 0.0000000000000000
Cost for Arc(PN9RD -PN-21D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-22D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-23D) = 1.0114042140279310E-06
Cost for Arc(PN9RD -PN-24D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-26 ) = 3.3590169341376450E-04
Cost for Arc(PN9RD -PN-27D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-28 ) = 1.2892920405072210E-04
Cost for Arc(PN9RD -PN-29D) = 6.4523924767727150E-05
Cost for Arc(PN9RD -PN-30D) = 1.8094525733757920E-06
Cost for Arc(PN9RD -PN-31D) = 1.0569171012670150E-05
```

```
Cost Coefficient for Injection WellOK12RD= 1.0000000000E-03
Cost Coefficient for Injection WellPN9RD = 7.0647304208E-03

These coefficients were scaled up by a factor of 2.52525342

              MAX       PHASE I     PHASE II
INJECTOR      INJ       ASSIGNED    ASSIGNED
  NAME        RATE        RATE        RATE
--------   --------   ---------   ---------

   OK12RD      165.        165.        165.
   PN9RD       101.         95.         95.
 Slack OK12RD                0.          0.
 Slack PNSRD                 6.          6.

Phase I Objective Function = 526.0000000000000
Phase I Fielduide Breakthrough Index = 0.8361493899783863
Phase II Fielduide Breakthrough Index = 0.8361493899783863

SOLVING FOR PRODUCTION RATES: ITERATION No. 2

Cost for Arc(OK12RD-OK-7  ) = 1.0302508836938890E-05
Cost for Arc(OK12RD-OK-9D ) = 0.0000000000000000
Cost for Arc(OK12RD-OK-10D) = 2.4188323247276310E-05
Cost for Arc(OK12RD-PN-13D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-14 ) = 0.0000000000000000
Cost for Arc(OK12RD-PN-15D) = 7.3393687207895330E-06
Cost for Arc(OK12RD-PN-16D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-17D) = 1.1327382218300400E-03
Cost for Arc(OK12RD-PN-18D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-19D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-20 ) = 0.0000000000000000
Cost for Arc(OK12RD-PN-21D) = 4.5268028204762410E-08
```

```
Cost for Arc(OK12RD-PN-22D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-23D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-24D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-26 ) = 3.1004805462167820E-08
Cost for Arc(OK12RD-PN-27D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-28 ) = 2.5215311981081780E-05
Cost for Arc(OK12RD-PN-29D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-30D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-31D) = 0.0000000000000000
Cost for Arc(PN9RD -OK-7  ) = 2.3885802651336980E-03
Cost for Arc(PN9RD -OK-9D ) = 0.0000000000000000
Cost for Arc(PN9RD -OK-10D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-13D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-14 ) = 0.0000000000000000
Cost for Arc(PN9RD -PN-15D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-16D) = 1.1432088398819640E-06
Cost for Arc(PN9RD -PN-17D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-18D) = 7.6560360750407440E-05
Cost for Arc(PN9RD -PN-19D) = 3.3869185252003540E-07
Cost for Arc(PN9RD -PN-20 ) = 0.0000000000000000
Cost for Arc(PN9RD -PN-21D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-22D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-23D) = 1.3216423704629090E-06
Cost for Arc(PN9RD -PN-24D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-26 ) = 3.3590169341376450E-04
Cost for Arc(PN9RD -PN-27D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-28 ) = 2.0724660549608470E-04
Cost for Arc(PN9RD -PN-29D) = 9.4304197737447360E-05
Cost for Arc(PN9RD -PN-30D) = 2.4075349365644290E-06
Cost for Arc(PN9RD -PN-31D) = 1,54472499415948303-05

Cost Coefficient for Producing WellOK-7  = 9.9175240443E-02
Cost Coefficient for Producing WellOK-9D = 0.0000000000
```

```
Cost Coefficient for Producing WellOK-10D= 1.0000000000E-03
Cost Coefficient for Producing WellPN-13D= 0.0000000000
Cost Coefficient for Producing WellPN-14 = 0.0000000000
Cost Coefficient for Producing WellPN-15D= 3.0342610540E-04
Cost Coefficient for Producing WellPN-16D= 4.72628395103-05
Cost Coefficient for Producing WellPN-17D= 4.68299604803-02
Cost Coefficient for Producing WellPN-18D= 3.16517850203-03
Cost Coefficient for Producing WellPN-19D= 1.40022873403-05
Cost Coefficient for Producing WellPN-20 = 0.0000000000
Cost Coefficient for Producing WellPN-21D= 1.8714826870E-06
Cost Coefficient for Producing WellPN-22D= 0.0000000000
Cost Coefficient for Producing WellPN-23D= 5.46396853103-05
Cost Coefficient for Producing WellPN-24D= 0.0000000000
Cost Coefficient for Producing WellPN-26 = 1.3888217660E-02
Cost Coefficient for Producing WellPN-27D= 0.0000000000
Cost Coefficient for Producing WellPN-28 = 9.6105015250E-03
Cost Coefficient for Producing WellPN-29D= 3.8987488620E-03
Cost Coefficient for Producing WellPN-30D= 9.95329404103-05
Cost Coefficient for Producing WellPN-31D= 6.3862425610E-04
```

These coefficients were scaled up by a factor of 41.3422621225

PRODUCER NAME	MAX PROD RATE	PHASE I ASSIGNED RATE	PHASE II ASSIGNED RATE
OK-7	88.	88.	0.
OK-9D	45.	45.	45.
OK-10D	52.	52.	52.
PN-13D	36.	36.	36.
PN-14	40.	40.	40.
PN-15D	72.	0.	72.

PN-16D	46.	0.	46.
PN-17D	54.	0.	0.
PN-18D	64.	64.	61.
PN-19D	66.	0.	66.
PN-20	50.	50.	50.
PN-21D	51.	51.	51.
PN-22D	73.	73.	73.
PN-23D	73.	73.	73.
PN-24D	49.	49.	49.
PN-26	95.	95.	0.
PN-27D	80.	80.	80.
PN-28	59.	59,	0.
PN-29D	65.	0.	0.
PN-30D	71.	71.	71.
PN-31D	65.	4.	65.
Slack OK-7		0.	88.
Slack OK-9D		0.	0.
Slack OK-10D		0.	0.
Slack PN-13D		0.	0.
Slack PN-14		0.	0.
Slack PN-15D		72.	0.
Slack PN-16D		46.	0.
Slack PN-17D		54.	54.
Slack PN-18D		0.	3.
Slack PN-19D		66.	0.
Slack PN-20		0.	0.
Slack PN-21D		0.	0.
Slack PN-22D		0.	0.
Slack PN-23D		0.	0.
Slack PN-24D		0.	0.
Slack PN-26		0.	95.
Slack PN-27D		0.	0.
Slack PN-28		0.	59.

```
Slack PN-29D            65.         65.
Slack PN-SOD             0.          0.
Slack PN-31D            61.          0.

Phase I Objective Function = 2223.400000000000
Phase I Fieldvide Breakthrough Index = 10.84304042994569
Phase II Fieldwide Breakthrough Index = 0.3231497417919218

SOLVING FOR INJECTION RATES: ITERATION No. 3

Cost for Arc(OK12RD-OK-7  ) = 0.0000000000000000
Cost for Arc(OK12RD-OK-9D ) = 0.0000000000000000
Cost for Arc(OK12RD-OK-10D) = 7.5496887711195760E-06
Cost for Arc(OK12RD-PN-13D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-14 ) = 0.0000000000000000
Cost for Arc(OK12RD-PN-15D) = 3.2026336236172510E-06
Cost for Arc(OK12RD-PN-16D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-17D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-18D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-19D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-20 ) = 0.0000000000000000
Cost for Arc(OK12RD-PN-21D) = 1.3991935990562930E-08
Cost for Arc(OK12RD-PN-22D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-23D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-24D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-26 ) = 0.0000000000000000
Cost for Arc(OK12RD-PN-27D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-28 ) = 0.0000000000000000
Cost for Arc(OK12RD-PN-29D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-30D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-31D) = 0.0000000000000000
Cost for Arc(PN9RD -OK-7  ) = 0.0000000000000000
Cost for Arc(PN9RD -OK-9D ) = 0.0000000000000000
```

```
Cost for Arc(PN9RD -OK-10D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-13D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-14 ) = 0.0000000000000000
Cost for Arc(PN9RD -PN-15D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-16D) = 5.5355375404810890E-07
Cost for Arc(PN9RD -PN-17D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-18D) = 4.9401580147368130E-05
Cost for Arc(PN9RD -PN-19D) = 2.3387563710857180E-07
Cost for Arc(PN9RD -PN-20 ) = 0.0000000000000000
Cost for Arc(PN9RD -PN-21D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-22D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-23D) = 1.0114042140279310E-06
Cost for Arc(PN9RD -PN-24D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-26 ) = 0.0000000000000000
Cost for Arc(PN9RD -PN-27D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-28 ) = 0.0000000000000000
Cost for Arc(PN9RD -PN-29D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-30D) = 1.8094525733757920E-06
Cost for Arc(PN9RD -PN-31D) = 1.0569171012670150E-05

Cost Coefficient for Injection WellOK12RD= 1.0000000000E-03
Cost Coefficient for Injection WellPN9RD = 5.90536699703-03

These coefficients were scaled up by a factor of 92.882296511
```

INJECTOR NAME	MAX INJ RATE	PHASE I ASSIGNED RATE	PHASE II ASSIGNED RATE
OK12RD	165.	165.	165.
PN9RD	101.	95.	95.
Slack OK12RD		0.	0.
Slack PN9RD		6.	6.

```
Phase I Objective Function = 526.0000000000000
Phase I Fieldwide Breakthrough Index = 0.7260098648084709
Phase II Fieldwide Breakthrough Index = 0.7260098648084709

Convergence Achieved in 3Iterations

Final Assigned Rates are Optimal for Injectors and Producers
Fortran STOP
```

Appendix C

Sample Output from Quadratic Programming

```
*****************************
*  OUTPUT FOR PROGRAM QPAL  *
*****************************

Number of Injectors = 2
Number of Producers = 21

Fieldwide Production Rate Required = 930.0000000000000
Fieldwide Injection Rate Required = 260.0000000000000

The following factors were used in the calculation
   of arc costs:
( 1) Reciprocal of Time to Peak Tracer Response
( 2) Fractional Tracer Recovery
( 3) Reciprocal of Production Rate During Tracer Tests
( 4) Reciprocal of Injection Rate During Tracer Tests
( 5) Exponential of Downhole Elevation Change
     from Producer to Injector

Cost for Arc(OK12RD-OK-7  ) = 6.2439447496599320E-08
Cost for Arc(OK12RD-OK-9D ) = 0.0000000000000000
Cost for Arc(OK12RD-OK-10D) = 1.4659589846834130E-07
Cost for Arc(OK12RD-PN-13D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-14 ) = 0.0000000000000000
Cost for Arc(OK12RD-PN-15D) = 4.4481022550239600E-08
Cost for Arc(OK12RD-PN-16D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-17D) = 6.8650801323032700E-06
Cost for Arc(OK12RD-PN-18D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-19D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-20D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-21D) = 2.7435168608946920E-10
Cost for Arc(OK12RD-PN-22D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-23D) = 0.0000000000000000
```

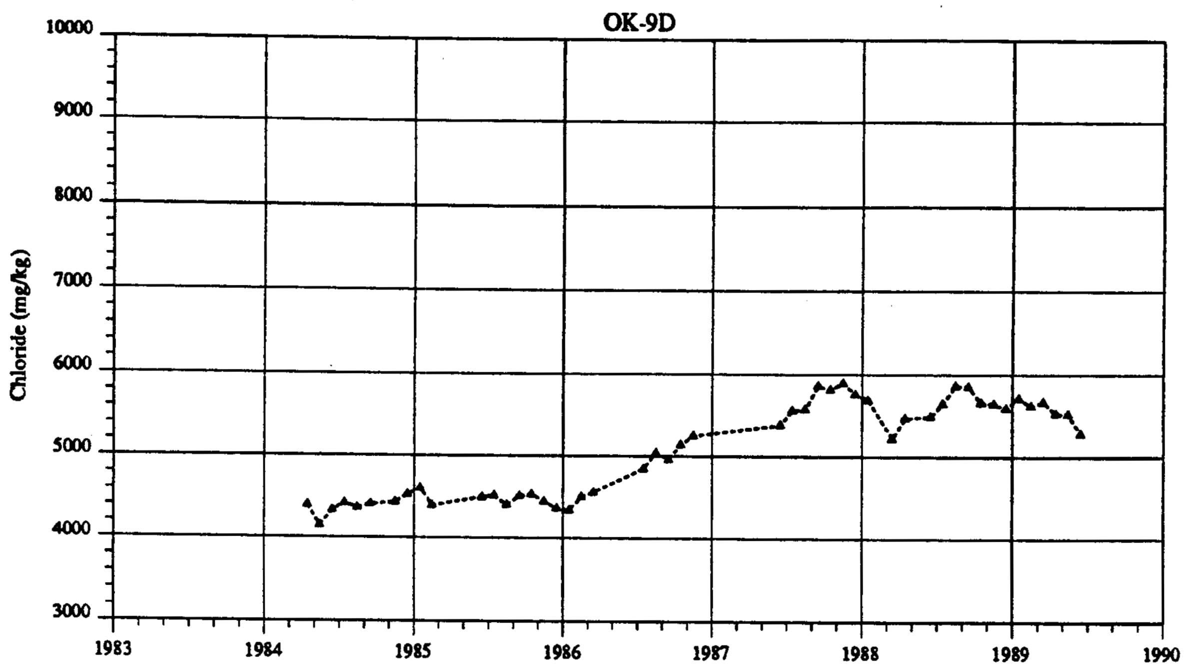
```
Cost for Arc(OK12RD-PN-24D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-26 ) = 1.8790791189192610E-10
Cost for Arc(OK12RD-PN-27D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-28 ) = 1.5282007261261690E-07
Cost for Arc(OK12RD-PN-29D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-30D) = 0.0000000000000000
Cost for Arc(OK12RD-PN-31D) = 0.0000000000000000
Cost for Arc(PN9RD -OK-7  ) = 2.5142950159302080E-05
Cost for Arc(PN9RD -OK-9D ) = 0.0000000000000000
Cost for Arc(PN9RD -OK-10D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-13D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-14 ) = 0.000000000000000
Cost for Arc(PN9RD -PN-15D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-16D) = 1.2033777261915410E-08
Cost for Arc(PN9RD -PN-17D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-18D) = 8.0589853421481510E-07
Cost for Arc(PN9RD -PN-19D) = 3.5651773949477410E-09
Cost for Arc(PN9RD -PN-20D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-21D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-22D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-23D) = 1.3912024952241150E-08
Cost for Arc(PN9RD -PN-24D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-26 ) = 3.5358072990922580E-06
Cost for Arc(PN9RD -PN-27D) = 0.0000000000000000
Cost for Arc(PN9RD -PN-28 ) = 2.1815432157482600E-06
Cost for Arc(PN9RD -PN-29D) = 9.9267576565734070E-07
Cost for Arc(PN9RD -PN-30D) = 2.5342473016467680E-08
Cost for Arc(PN9RD -PN-31D) = 1.6260263096415610E-07
```

INJECTOR NAME	MAX INJ RATE	MIN INJ RATE	ASSIGNED INJ RATE	SLACK
OK12RD	165.	0.	165.	0.

```
   PN9RD       101.        0.        95.          6.

                MAX       MIN     ASSIGNED
 PRODUCER      PROD      PROD       PROD
   NAME        RATE      RATE       RATE       SLACK
 ---------   --------  --------  ----------  --------

   OK-7         88.        0.         0.        88.
   OK-9D        45.        0.        45.         0.
   OK-10D       52.        0.        52.         0.
   PN-13D       36.        0.        36.         0.
   PN-14        40.        0.        40.         0.
   PN-15D       72.        0.        72.         0.
   PN-16D       46.        0.        46.         0.
   PN-17D       54.        0.         0.        54.
   PN-18D       64.        0.        61.         3.
   PN-19D       66.        0.        66.         0.
   PN-20D       50.        0.        50.         0.
   PN-21D       51.        0.        51.         0.
   PN-22D       73.        0.        73.         0.
   PN-23D       73.        0.        73.         0.
   PN-24D       49.        0.        49.         0.
   PN-26        95.        0.         0.        95.
   PN-27D       80.        0.        80.         0.
   PN-28        59.        0.         0.        59.
   PN-29D       65.        0.         0.        65.
   PN-SOD       71.        0.        71.         0.
   PN-31D       65.        0.        65.         0.

 EXIT QPSOL - OPTIMAL QP SOLUTION.

 FINAL VALUE OF FIELDWIDE BREAKTHROUGH INDEX =   0.7816450E-02
Fortran STOP
```

Appendix D

Reservoir Chloride Measurements with Time



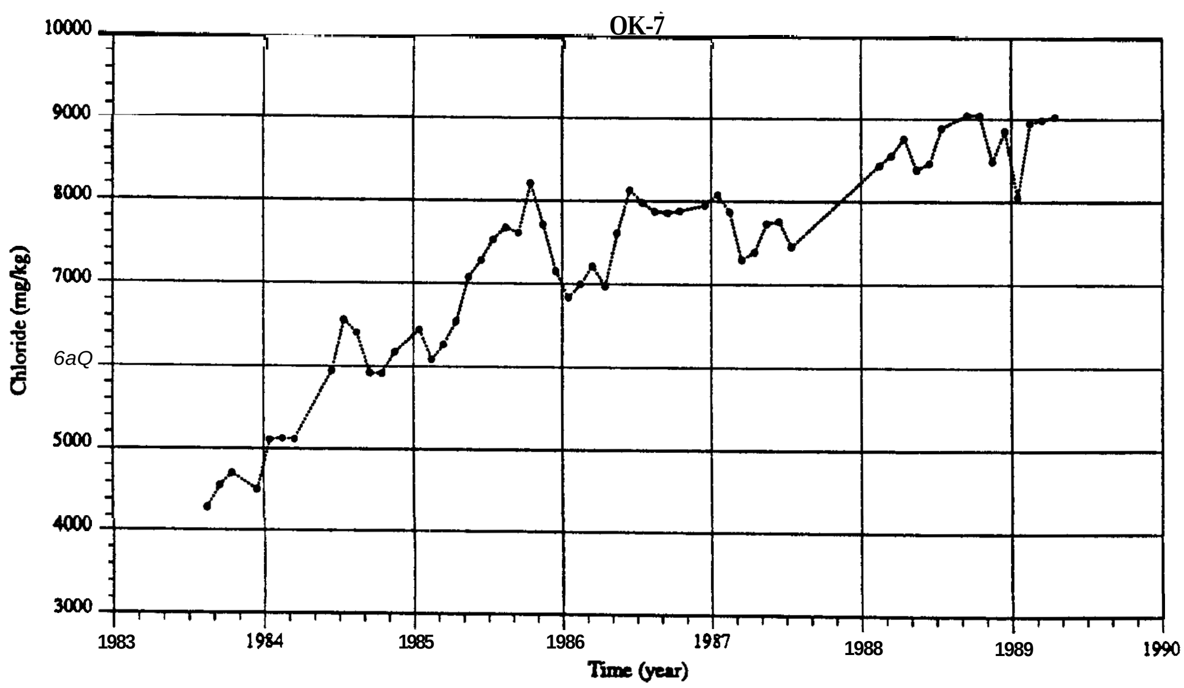
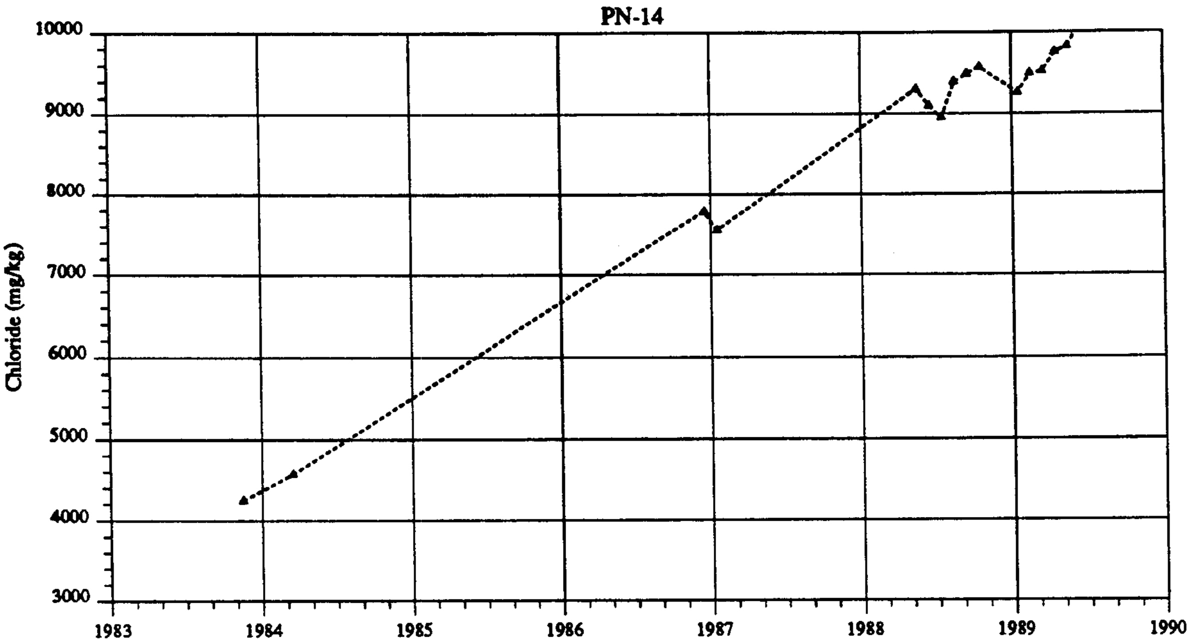


Figure D.l: OK-7/OK-9D Reservoir chloride with **time.**



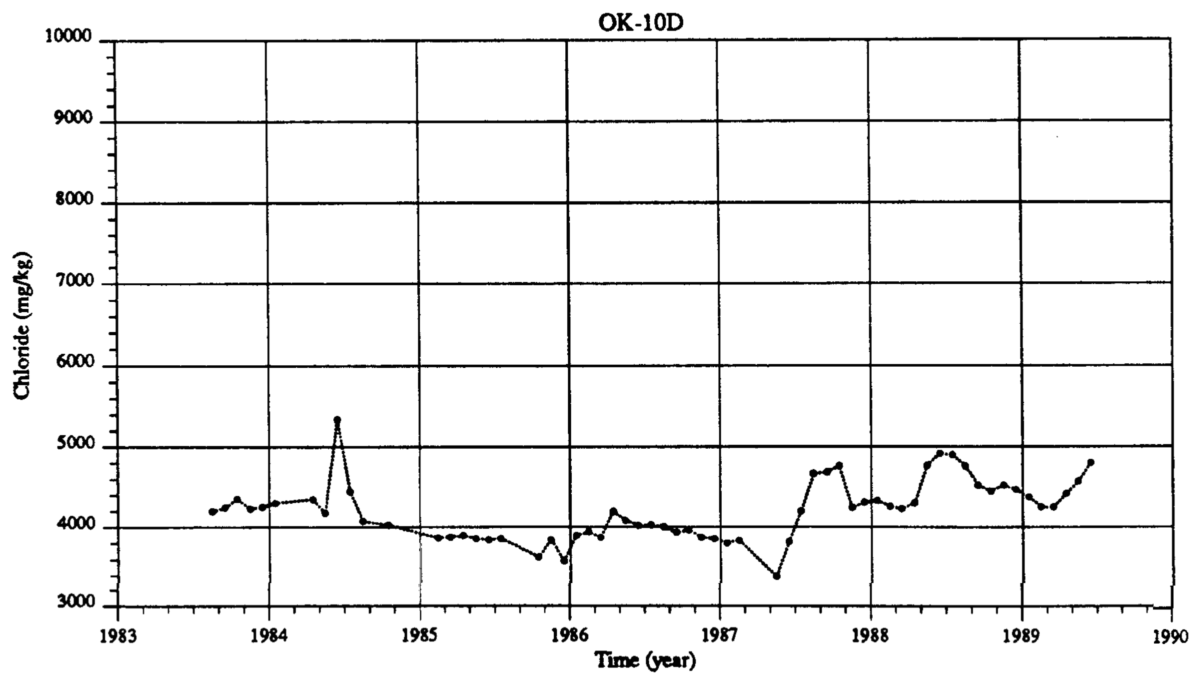


Figure D.2: OK-10D/PN-14 Reservoir **chloride with time.**

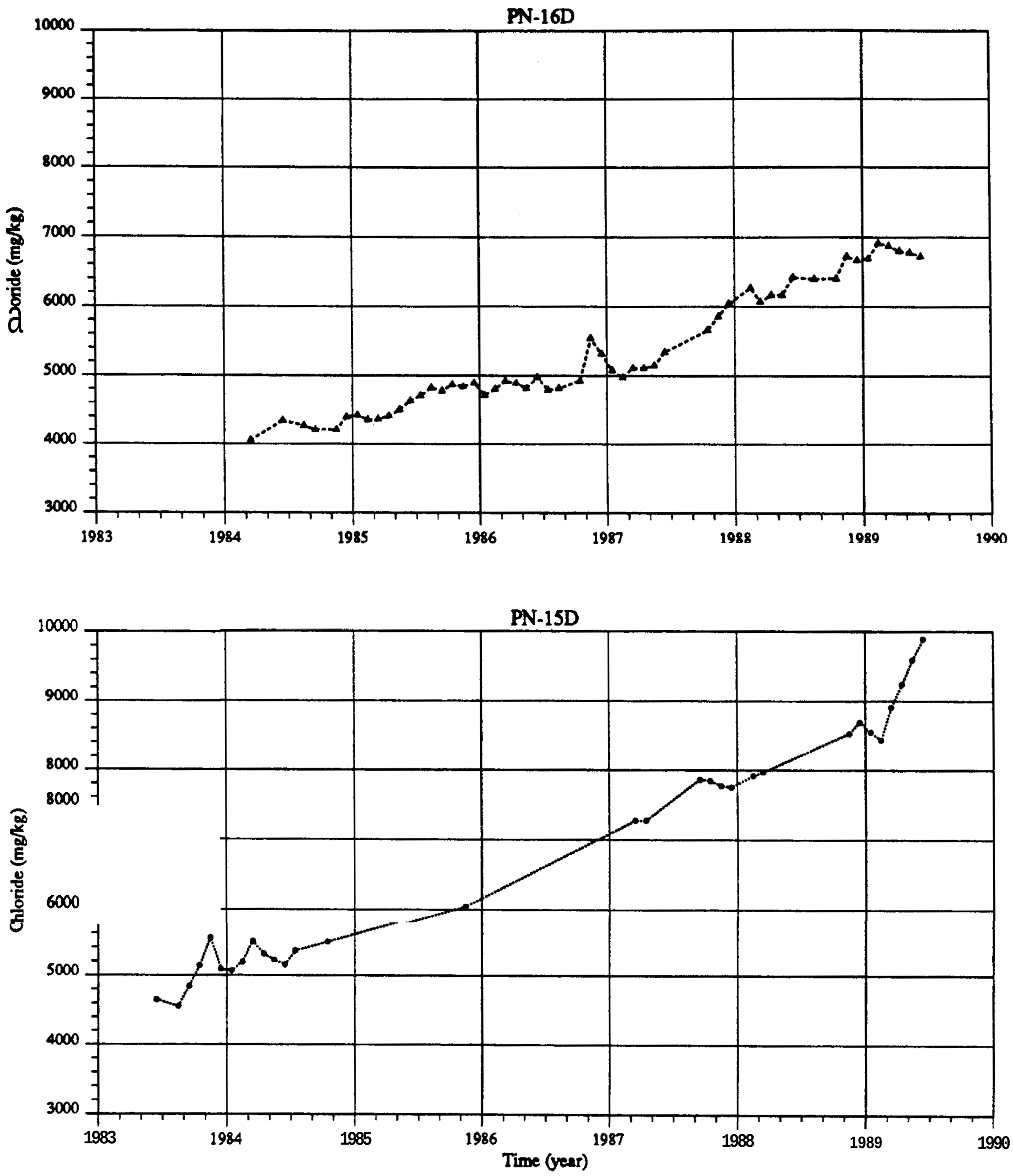


Figure D.3: PN-15D/PN-16D Reservoir chloride with time.

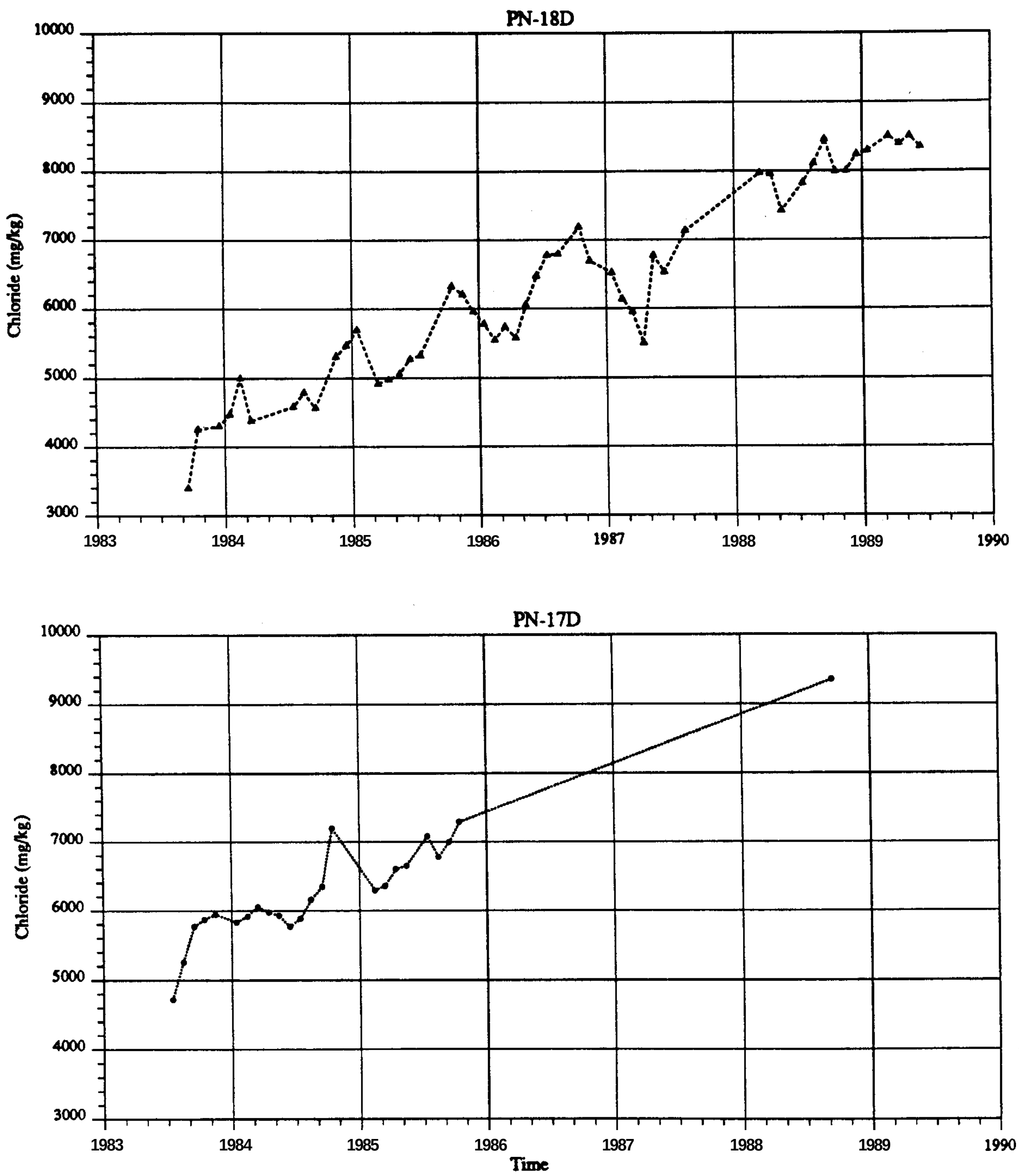
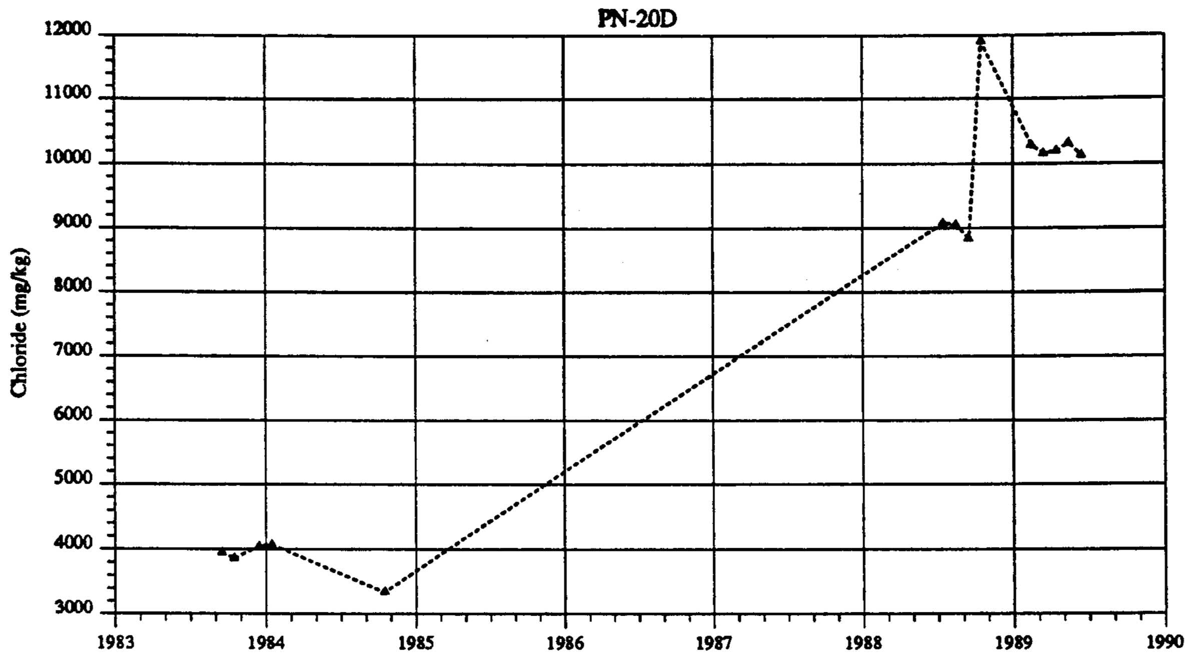


Figure D.4: PN-17D/PN-18D Reservoir chloride with time.



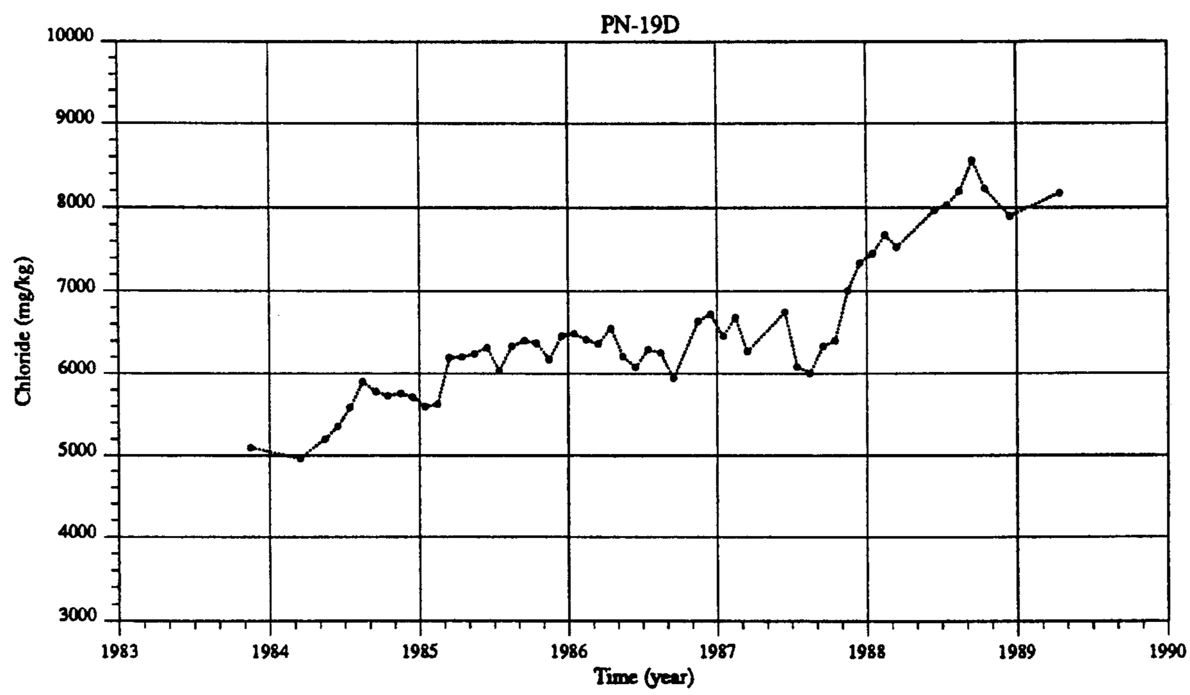


Figure D.5: PN-19D/PN-20D Reservoir chloride with time.

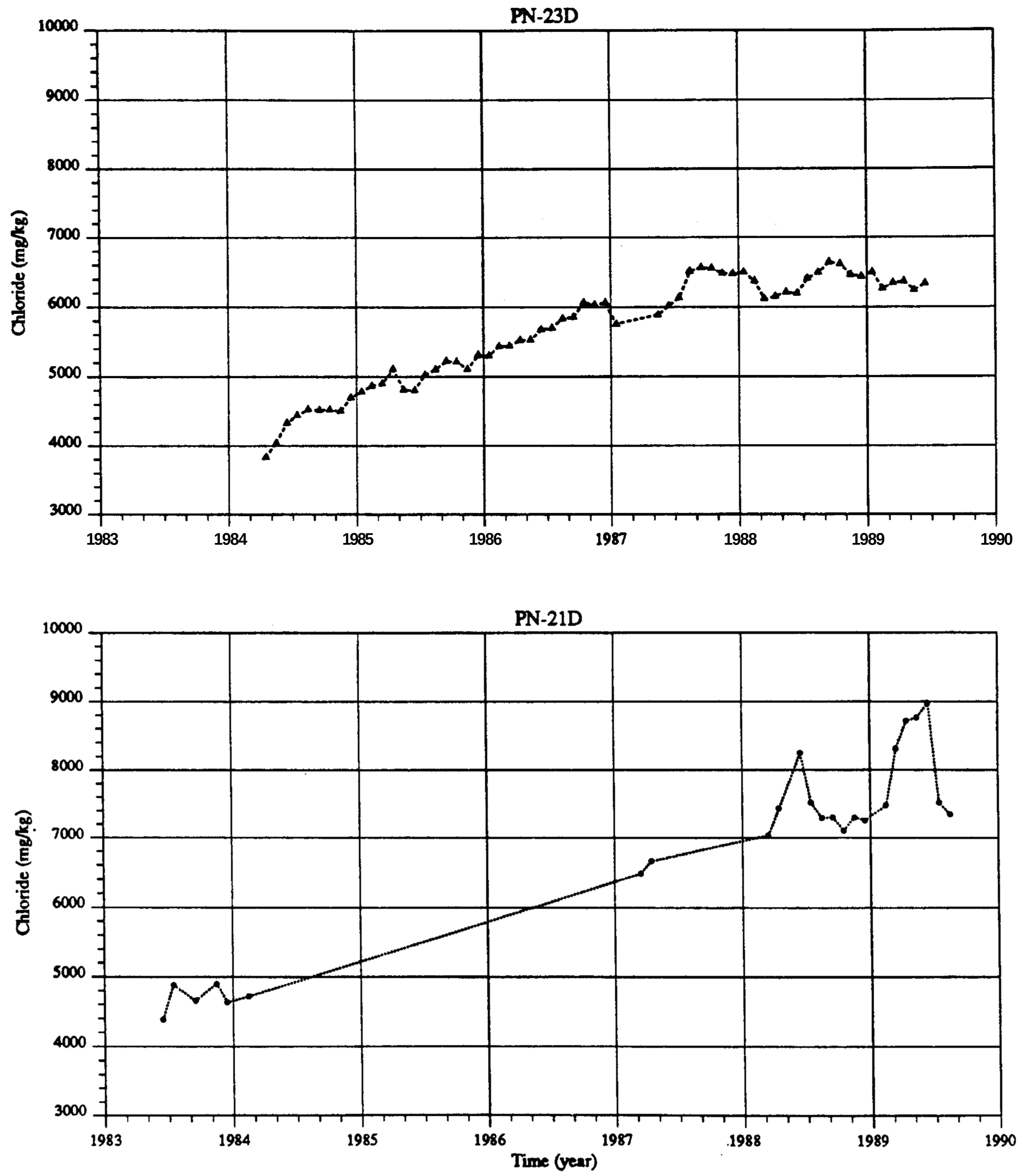
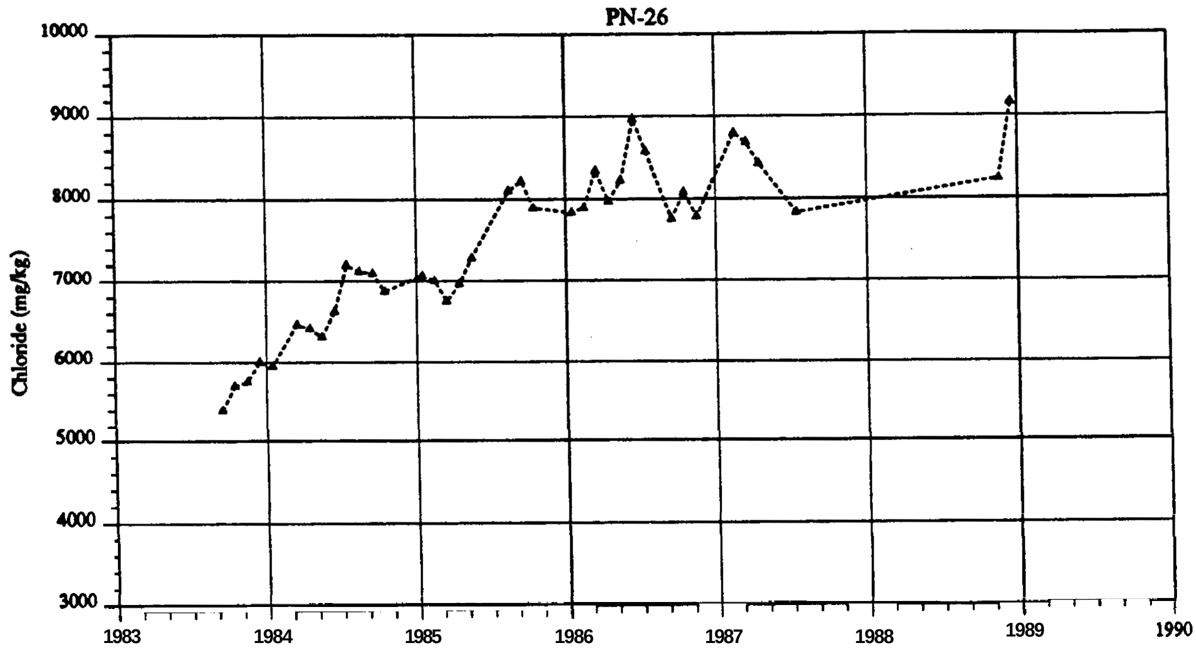


Figure D.6: PN-21D/PN-23D Reservoir **chloride with time.**



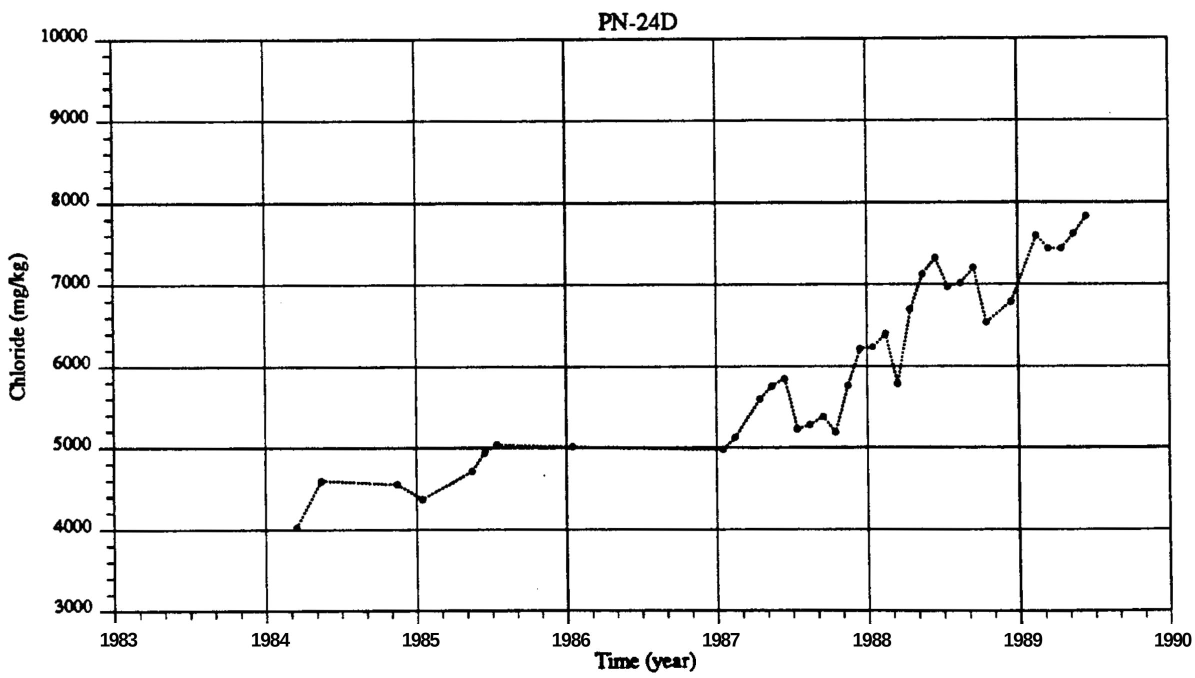


Figure D.7: PN-24D/PN-26 Reservoir chloride with time.

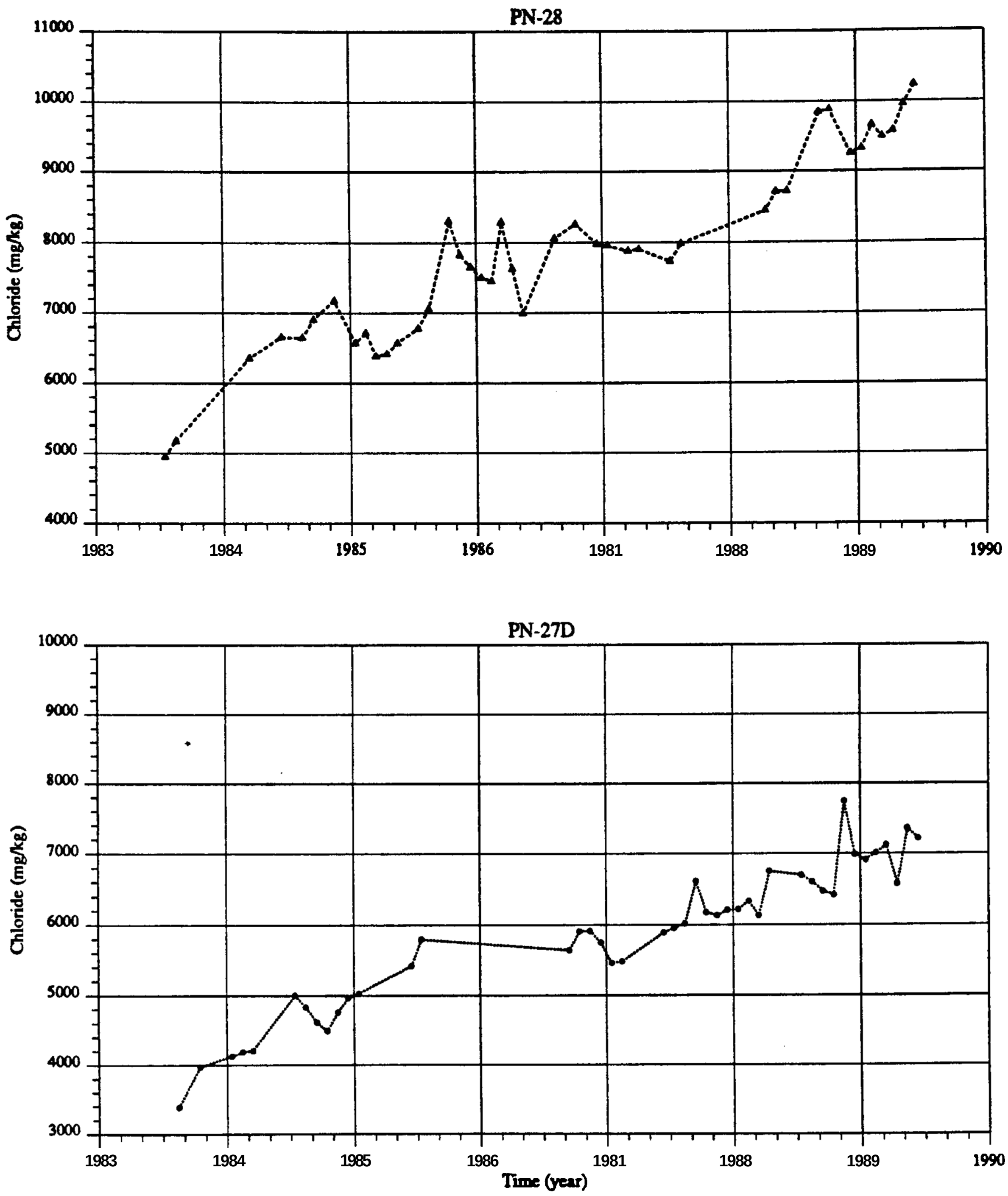


Figure D.8: PN-27D/PN-28 **Reservoir chloride with** time.

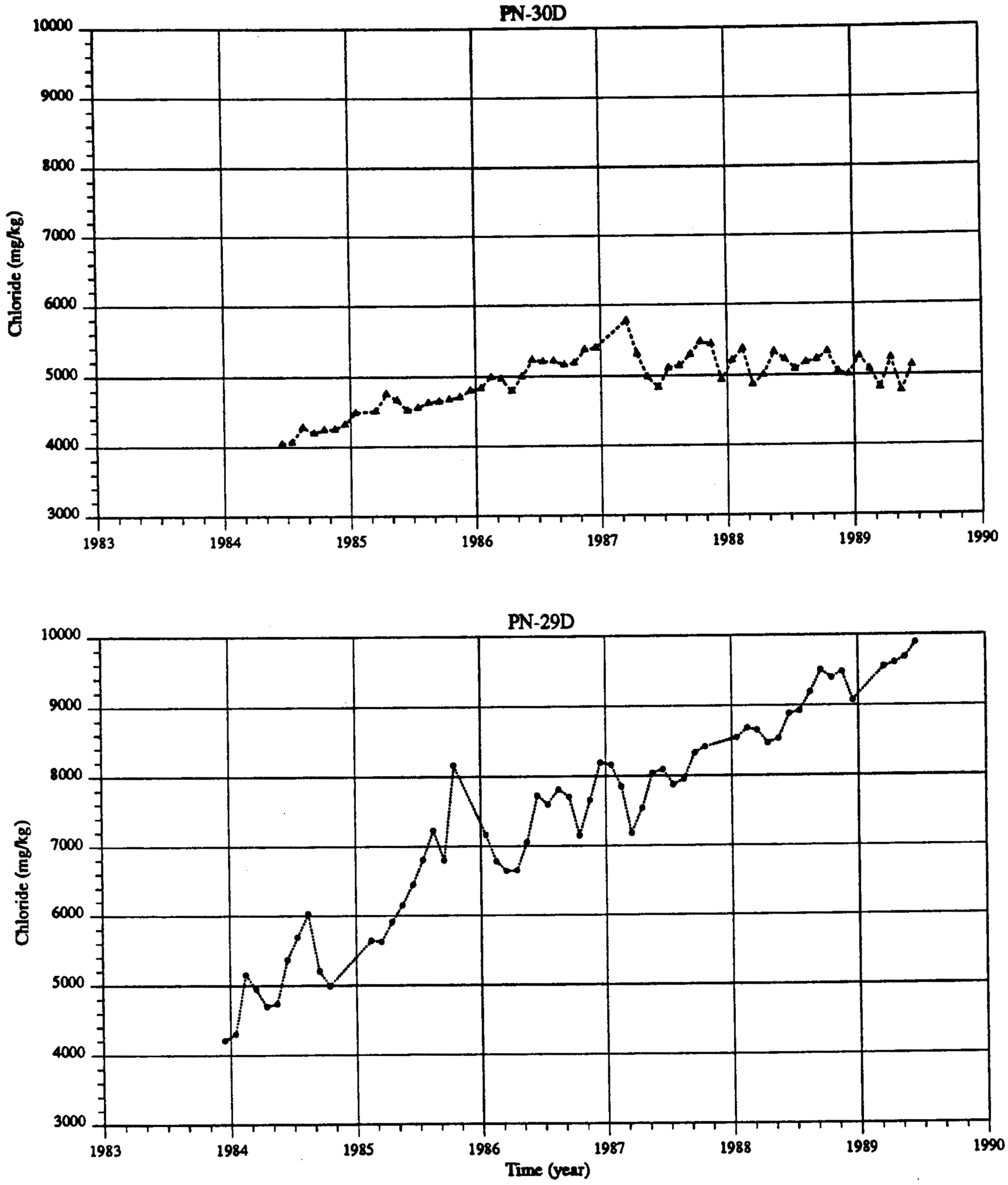


Figure D.9: PN-29D/PN-30D Reservoir chloride with time.

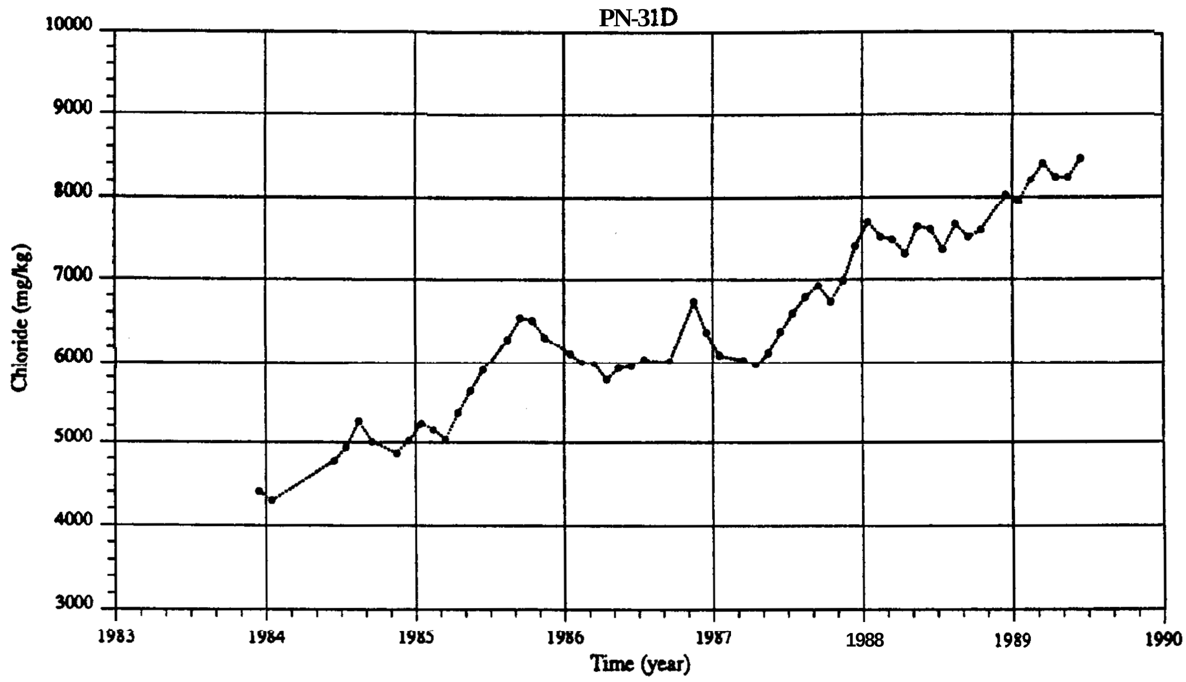


Figure D.lO: **PN-31D** Reservoir chloride with time.

Appendix E

Injection Flowrates with Time

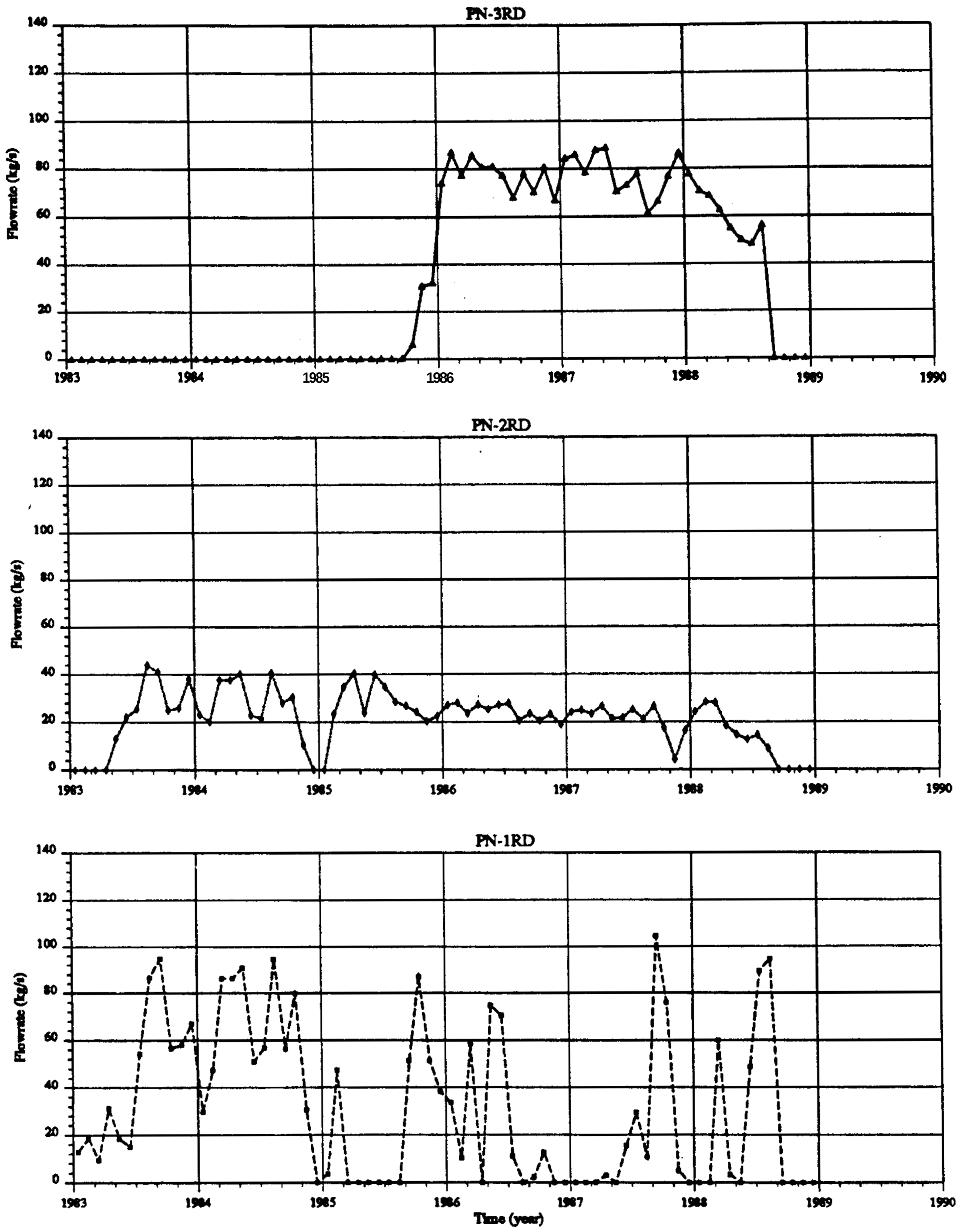


Figure E.1: PN-1RD/PN-2RD/PN-3RD Injection **flowrates** with **time.**

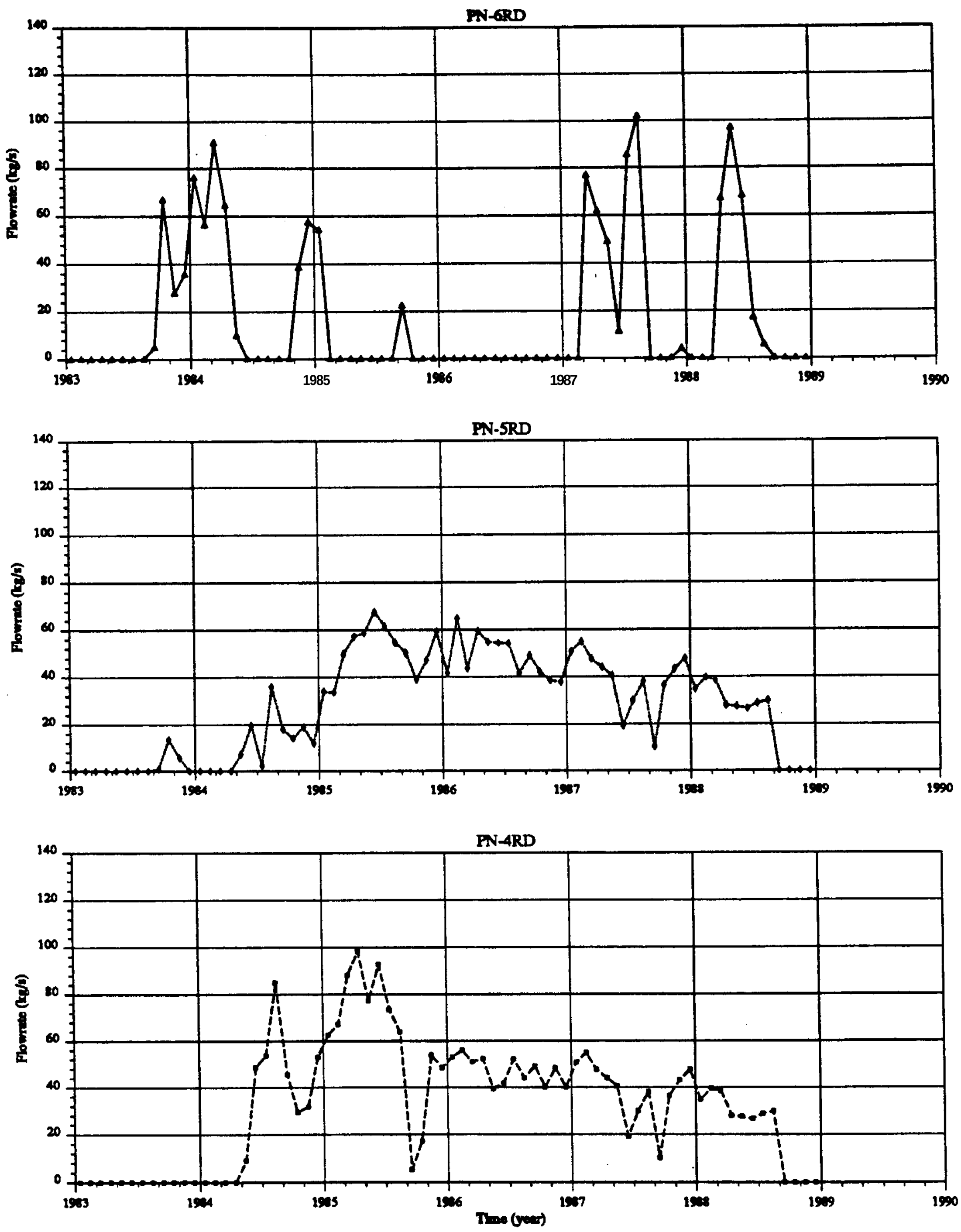


Figure E.2: PN-4RD/PN-5RD/PN-6RD Injection flowrates with time.

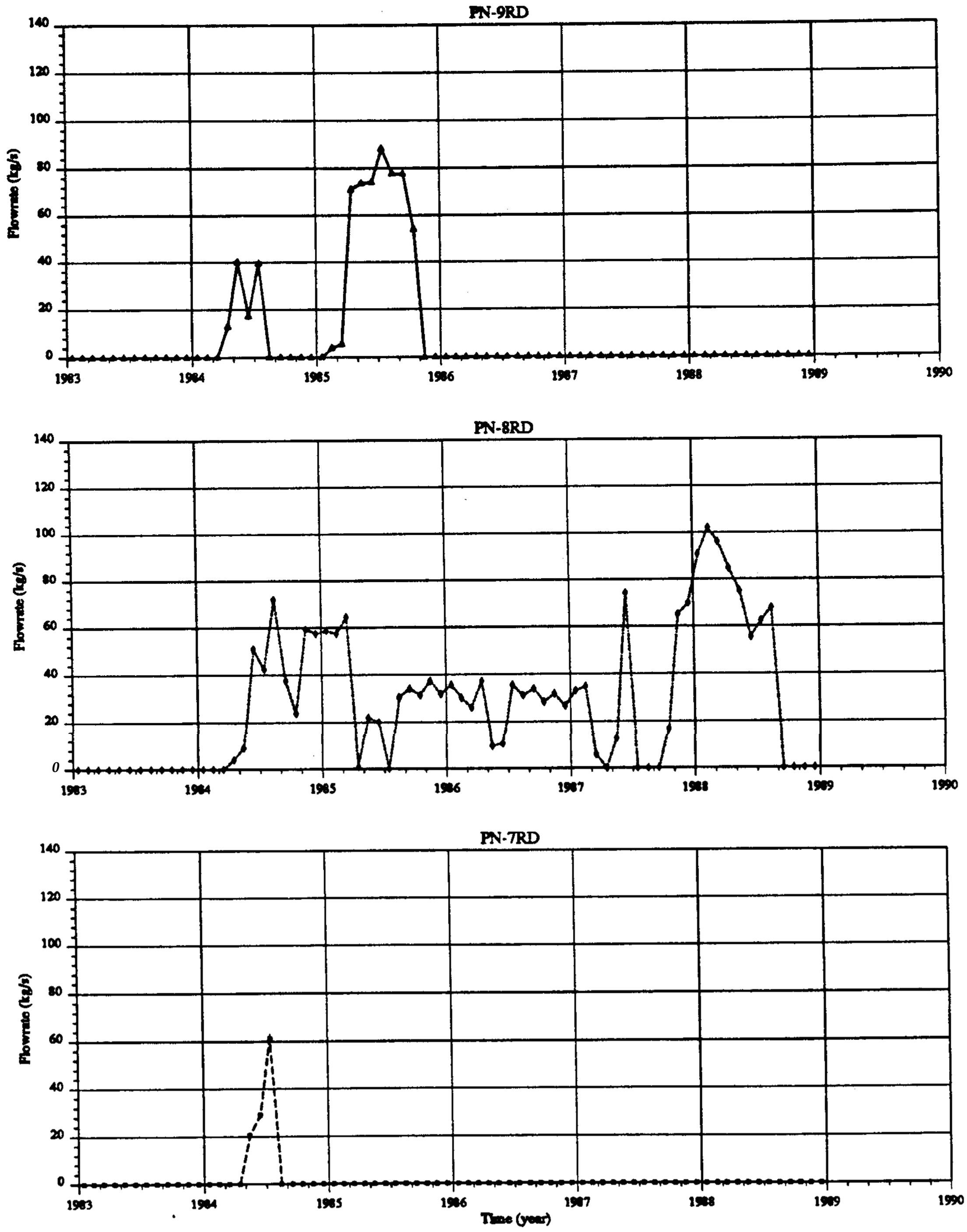


Figure E.3: PN-7RD/PN-8RD/PN-9RD Injection flowrates with time.

Appendix F

Chloride-Flow Correlations

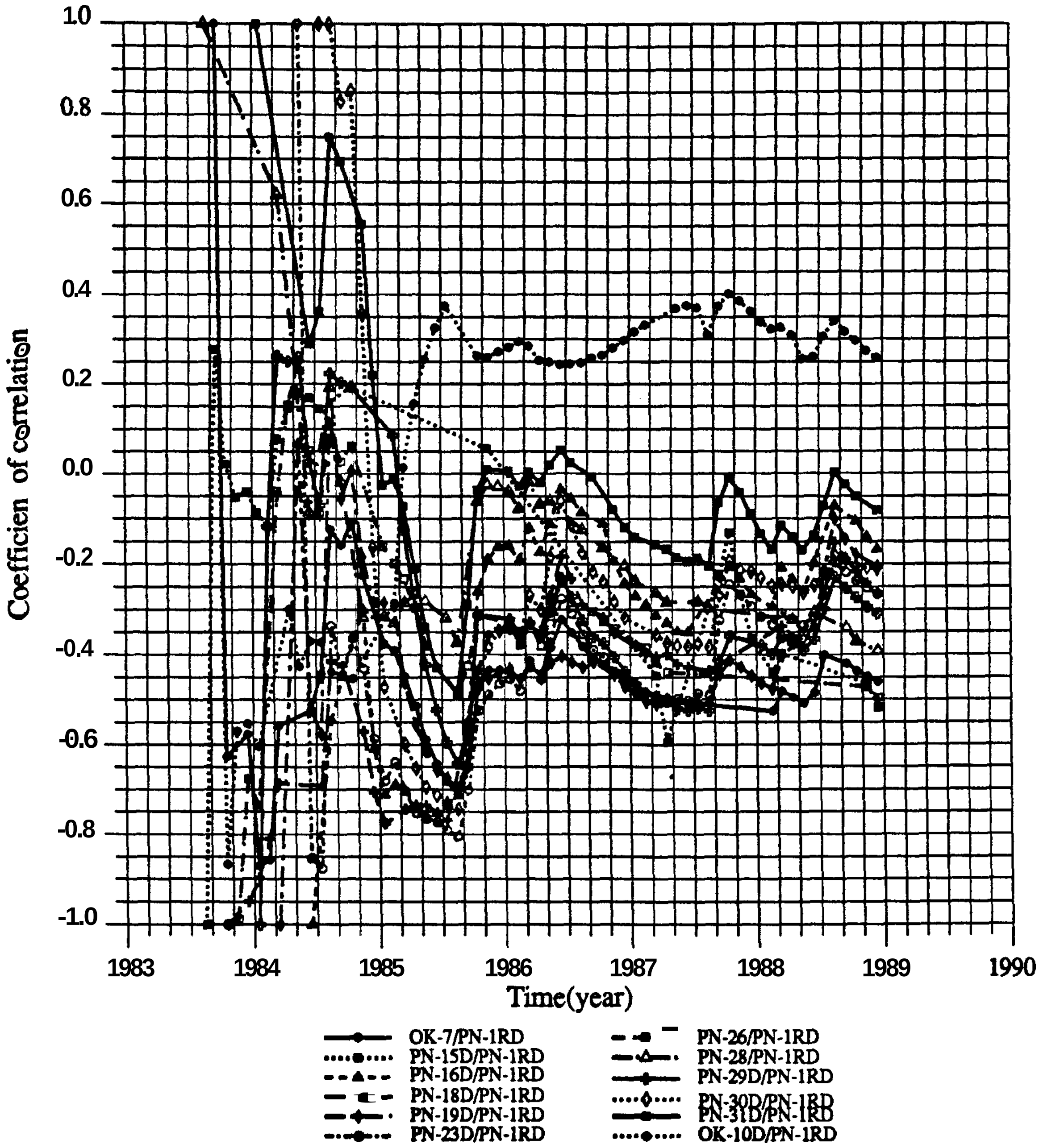


Figure F.1: PN-1RD Chloride-flow correlations with time.

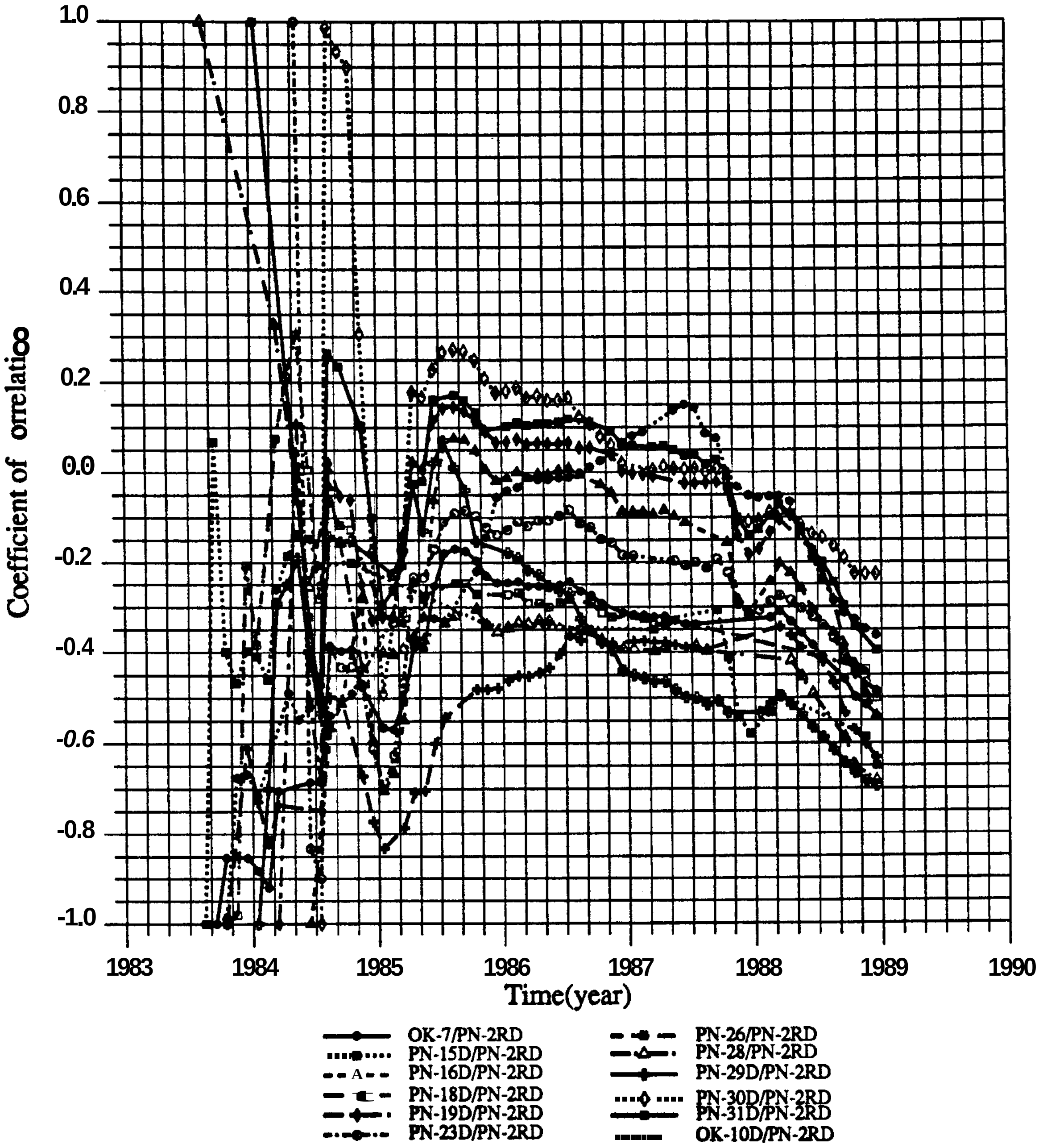


Figure F.2: PN-2RD **Chloride-flow correlations with time.**

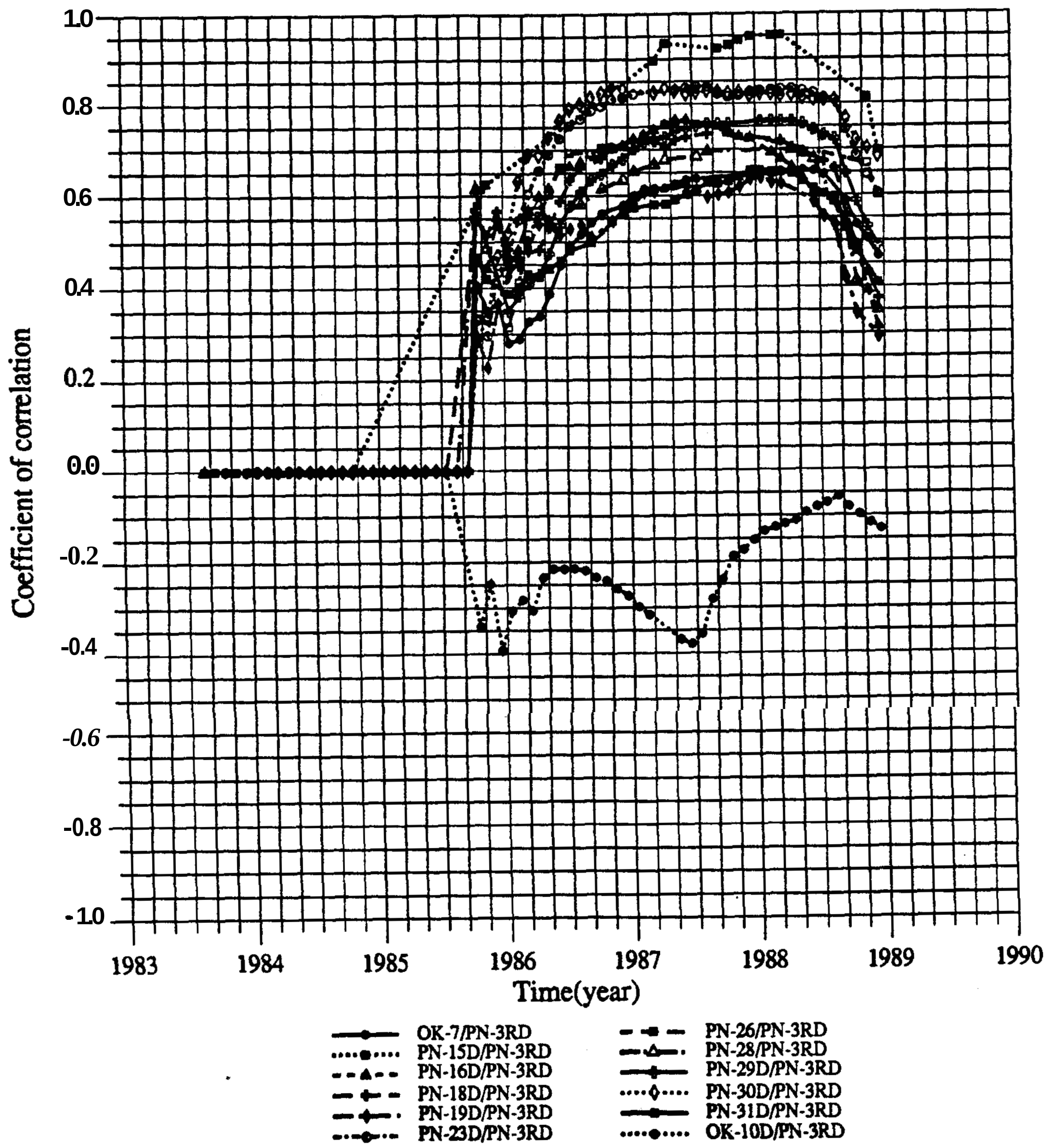


Figure F.3: **PN-3RD** Chloride-flow correlations with time.

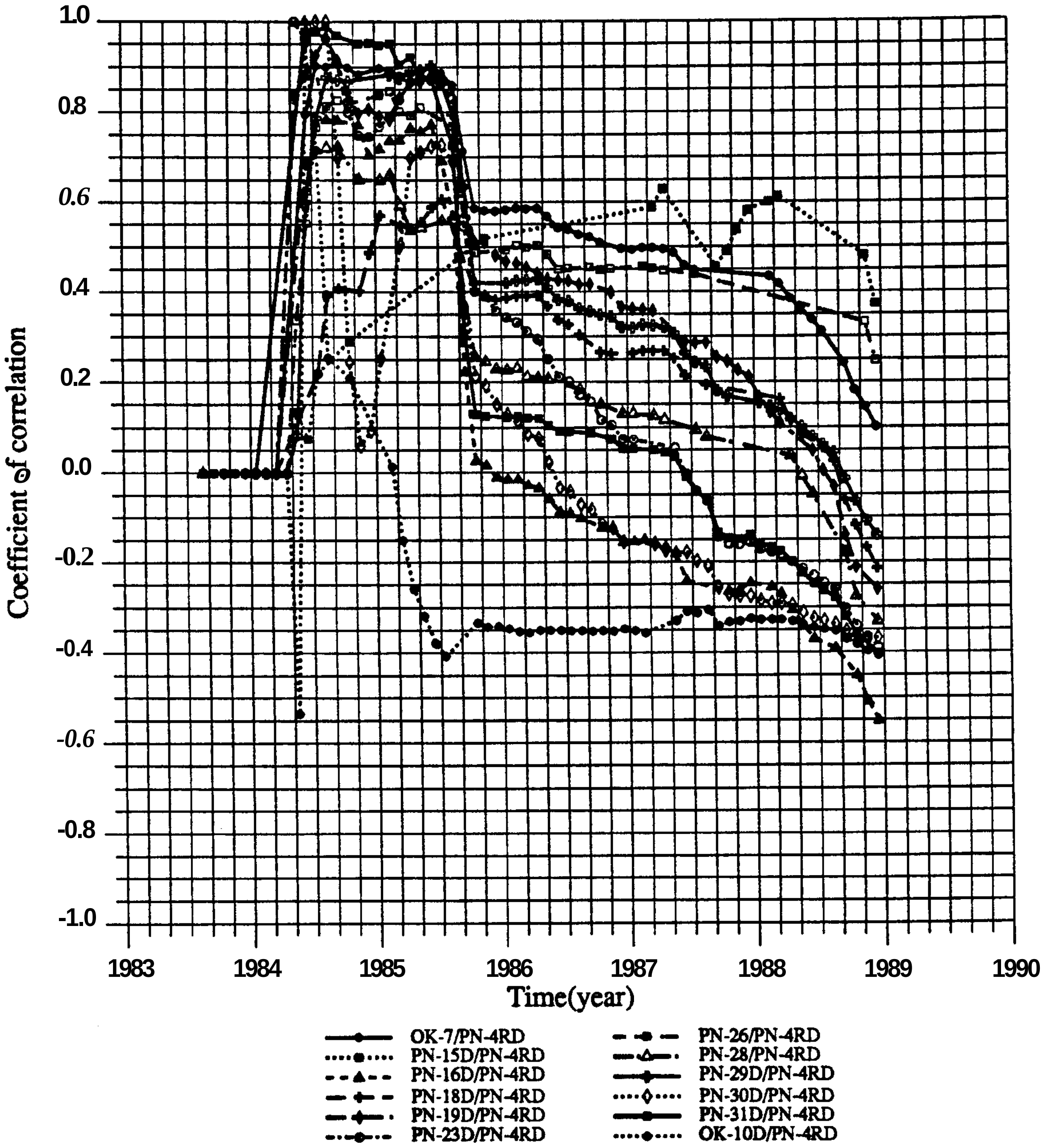


Figure F.4: PN-4RD Chloride-flow correlations with time.

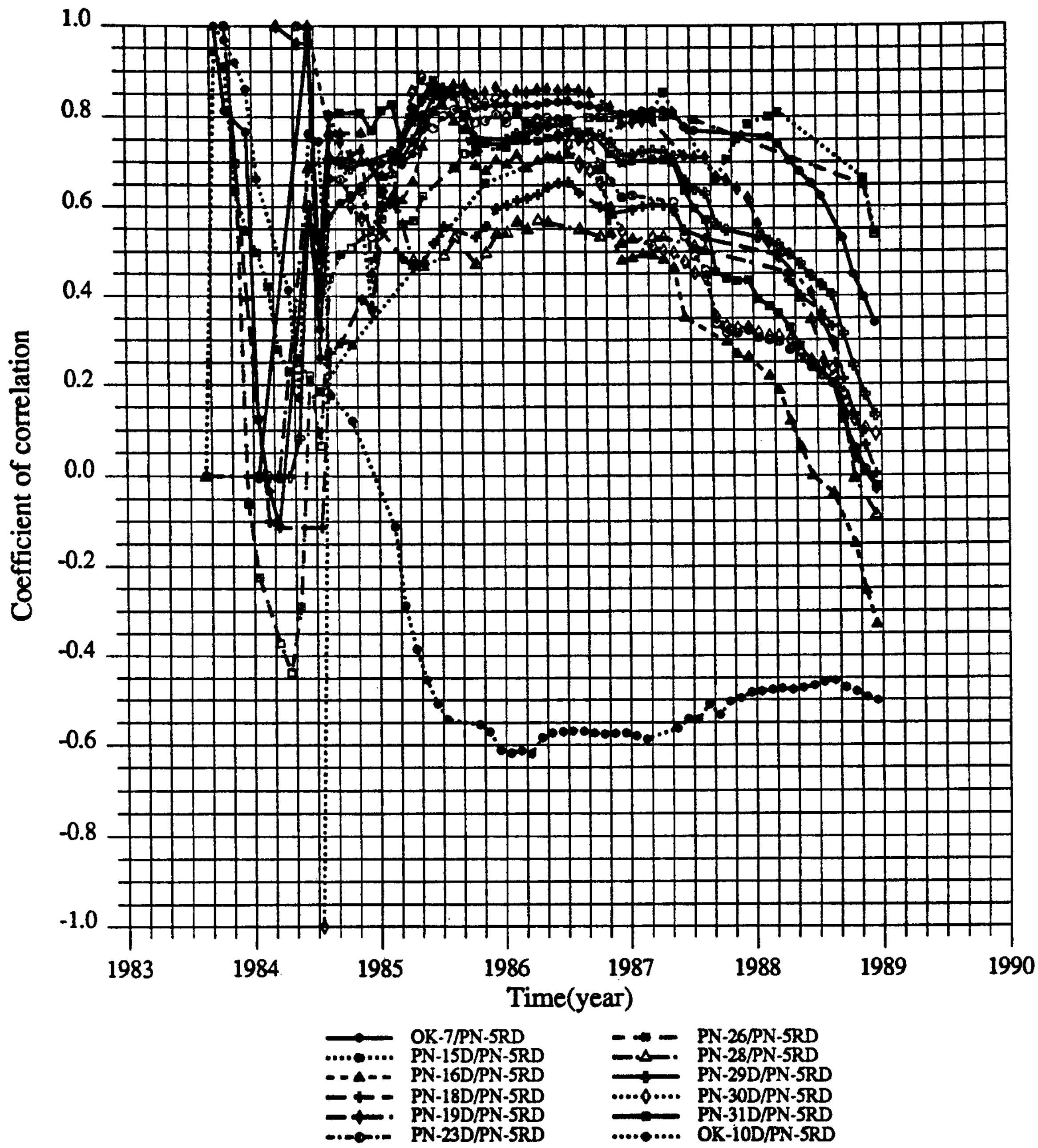


Figure F.5: PN-5RD **Chloride-flow correlations with time.**

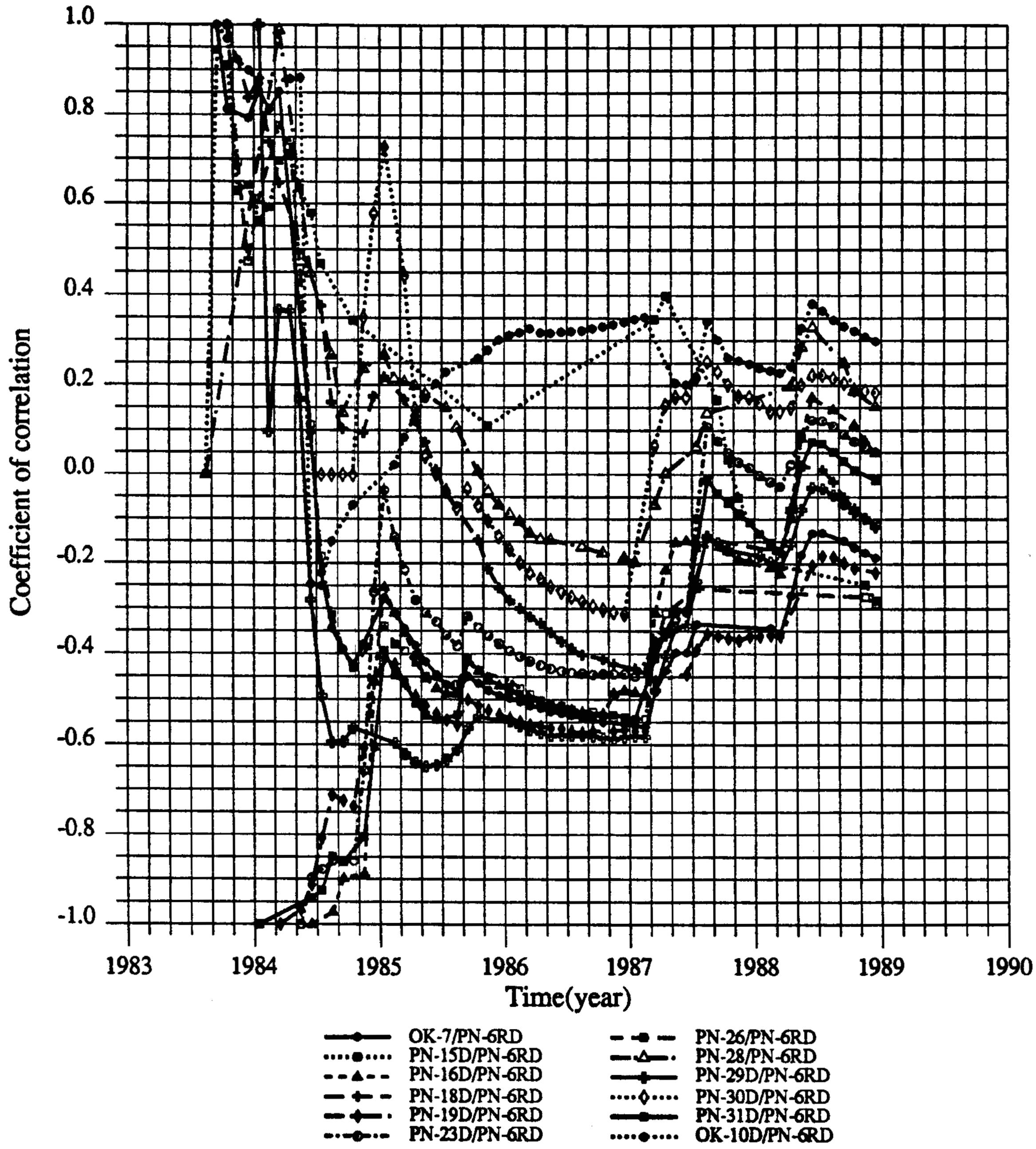


Figure F.6: PN-6RD **Chloride-flow correlations with time.**

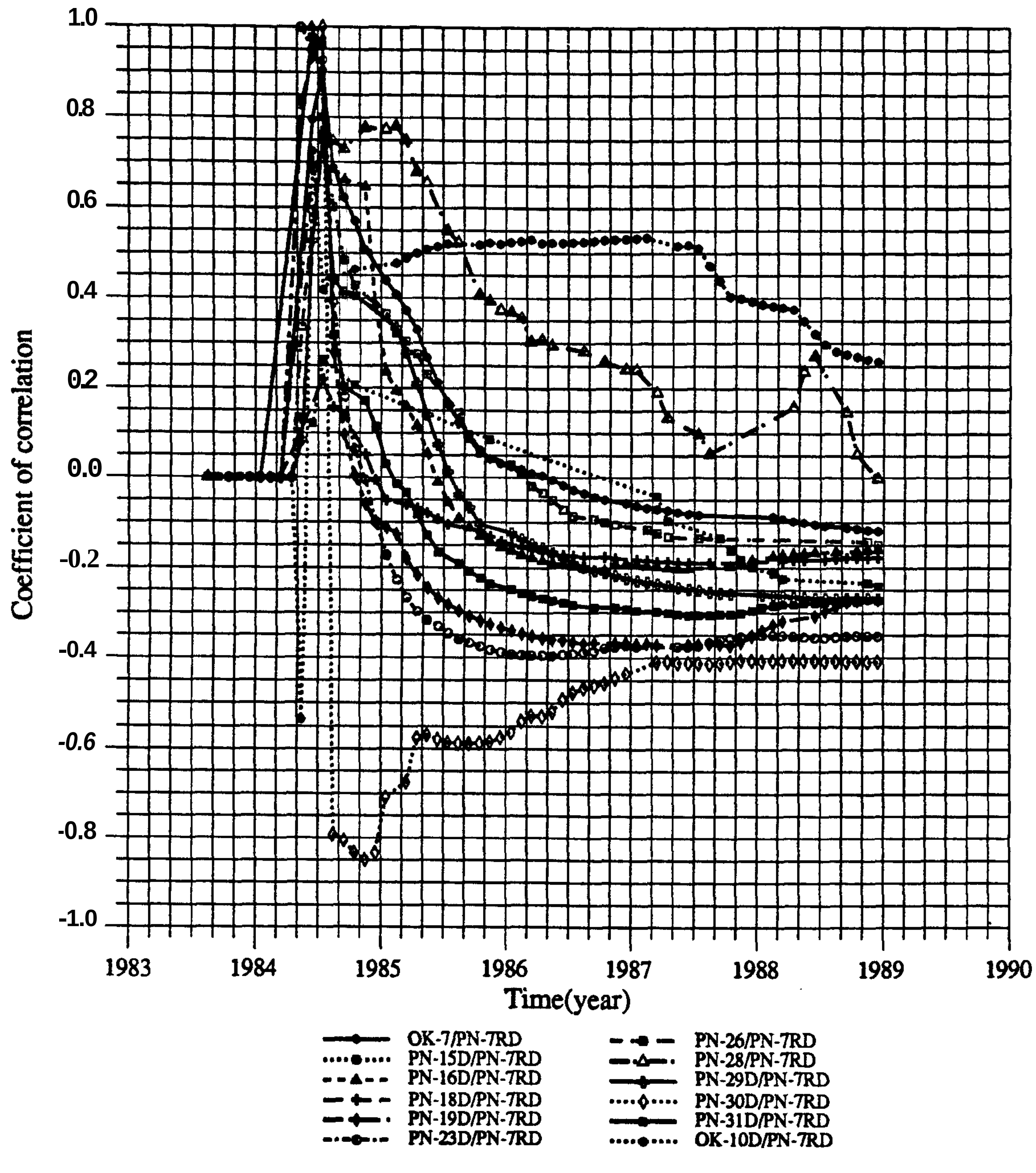


Figure F.7: PN-7RD Chloride-flow correlations with time.

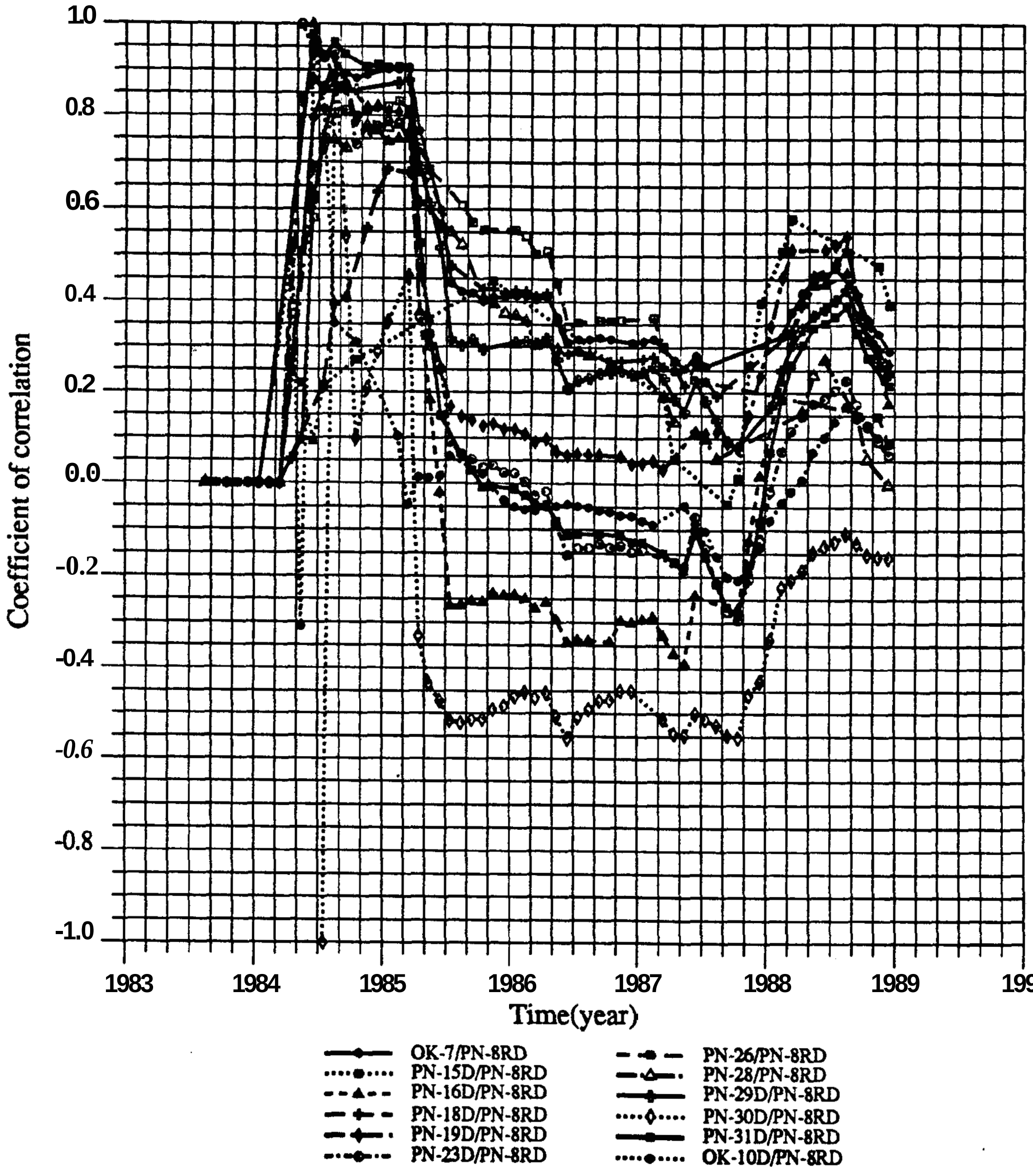


Figure F.8: PN-8RD Chloride-flow correlations with time.

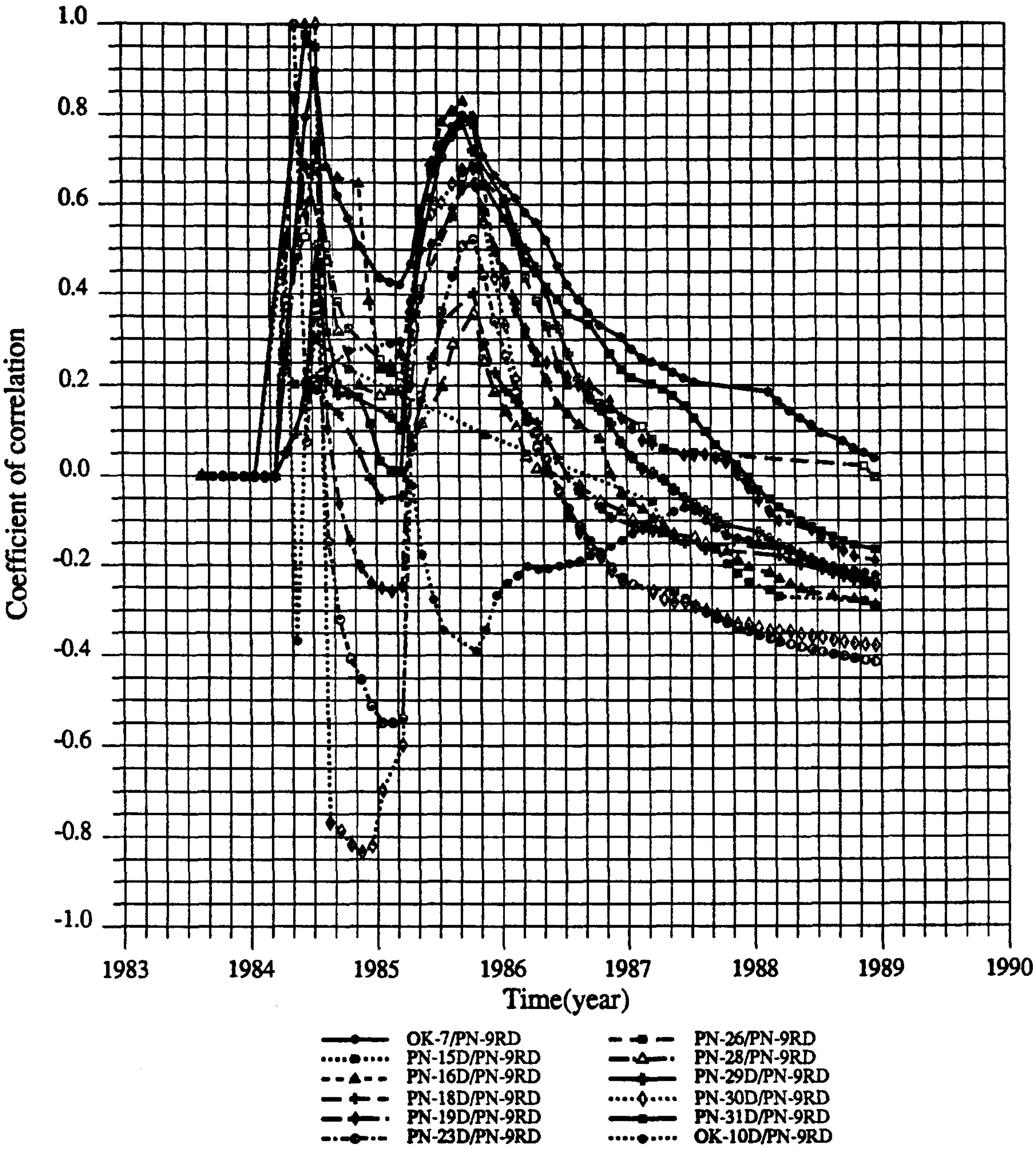


Figure F.9: PN-9RD Chloride-flow correlations with time.

Appendix *G*

Chloride Shift-Flow Correlation

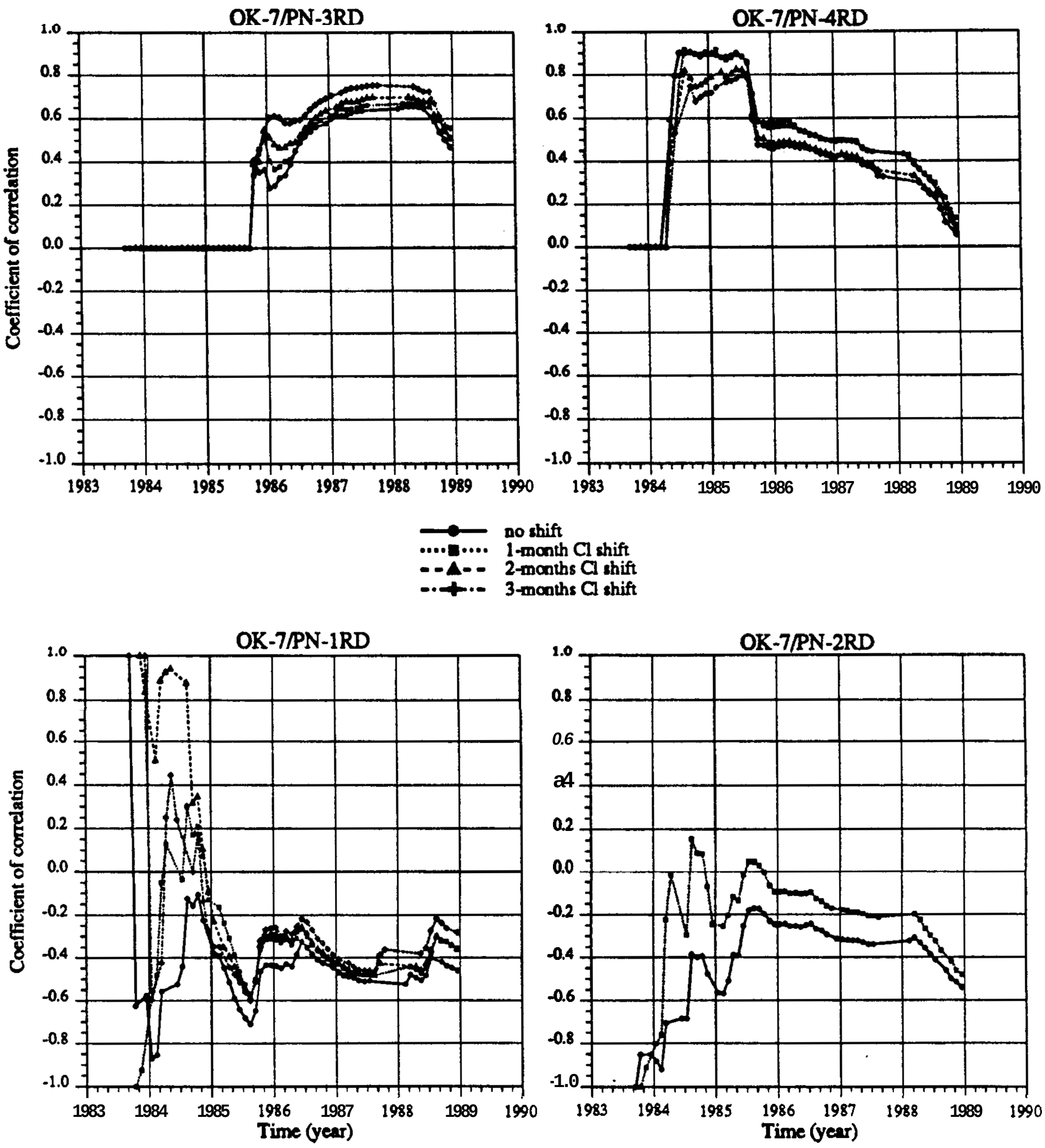


Figure G.1: OK-7 chloride shift-flow correlation

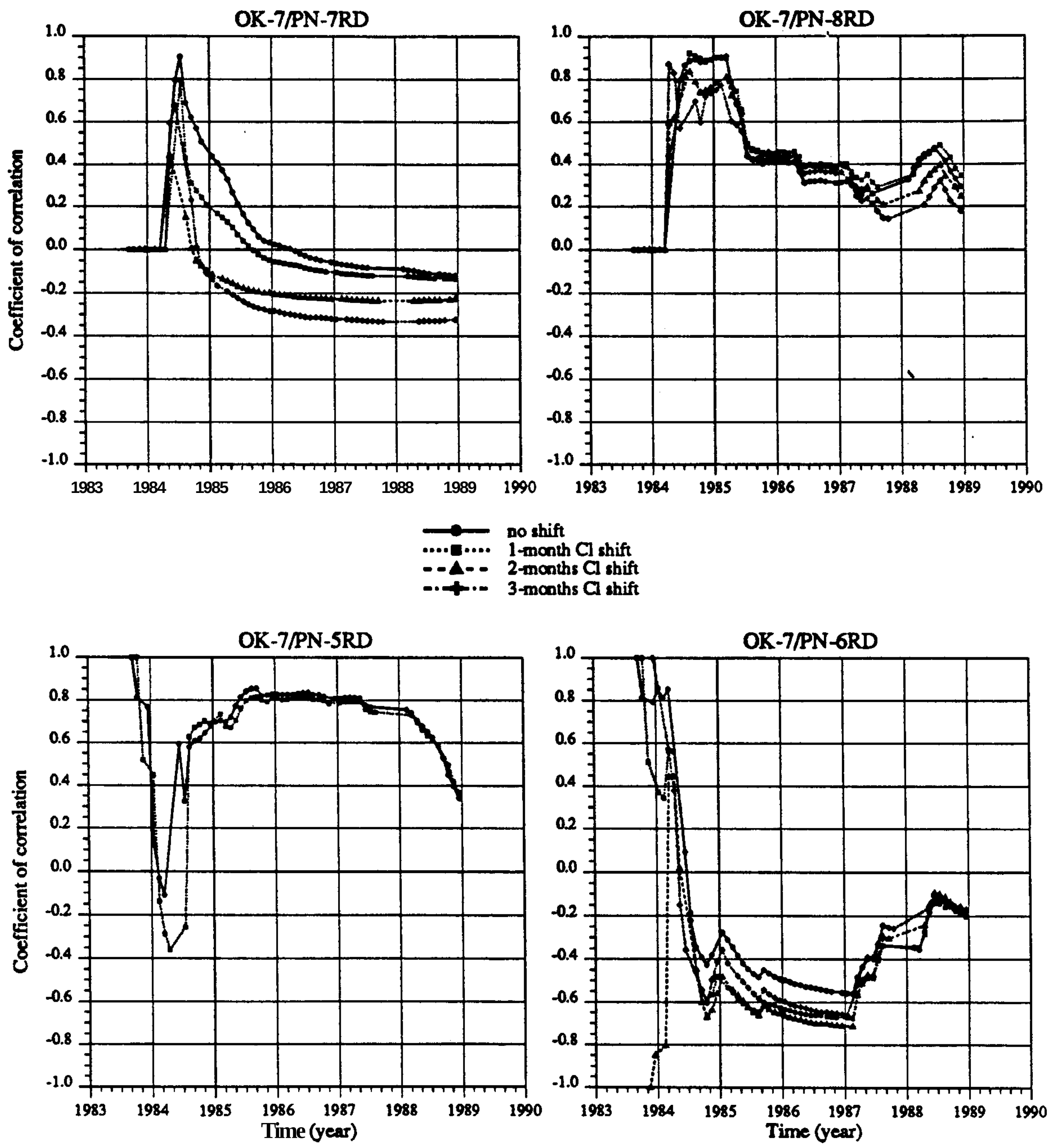


Figure G.2: OK-7 chloride shift-flow correlation

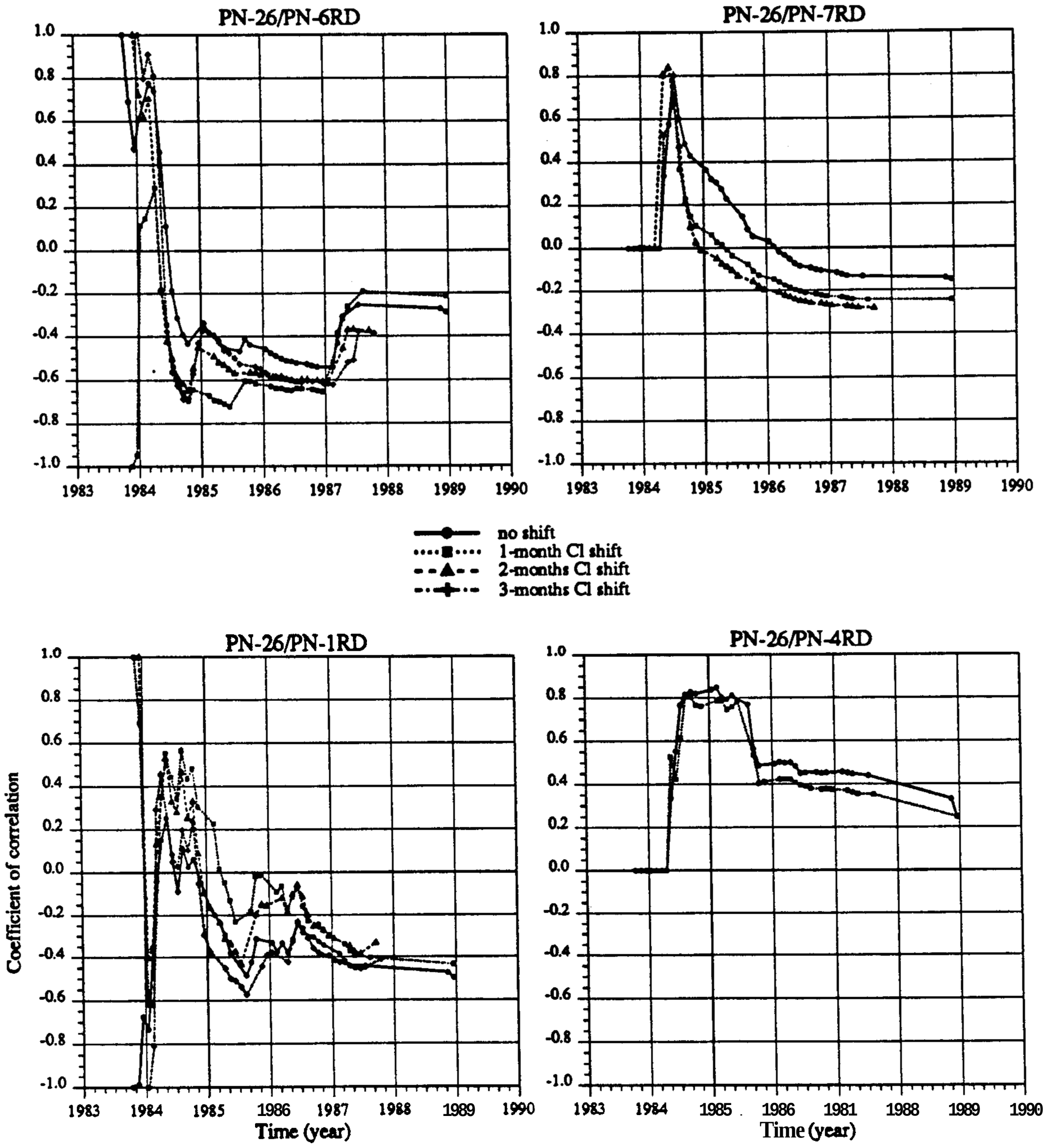


Figure G.3: PN-26 chloride shift-flow correlation

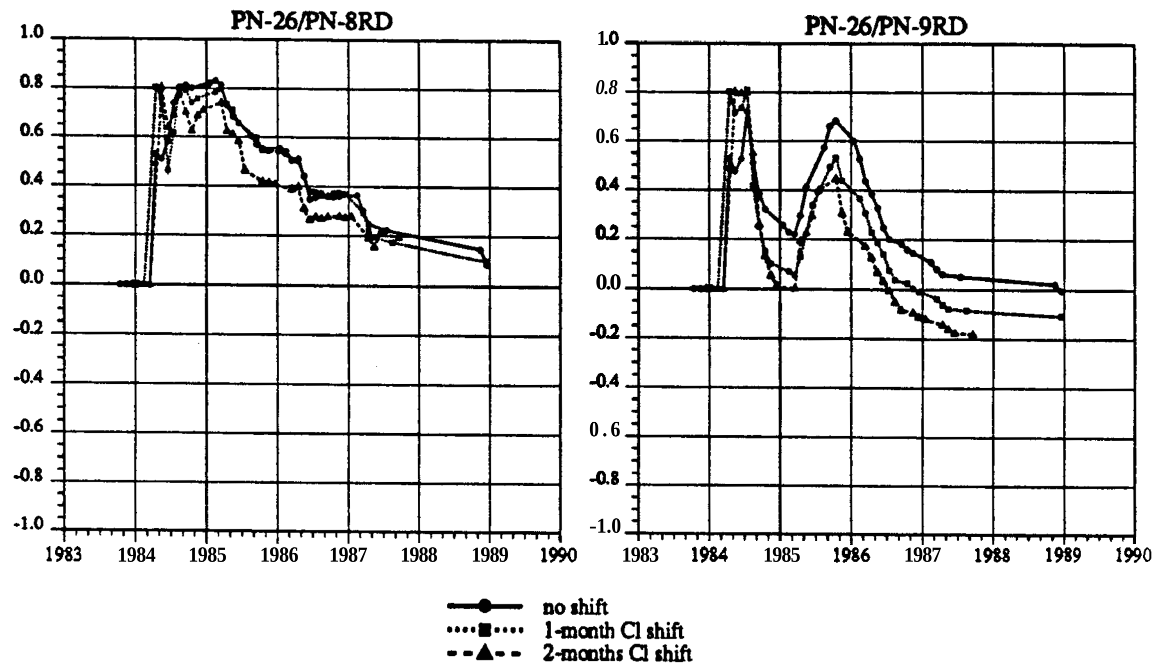


Figure **G.4: PN-26** chloride **shift-flow** correlation

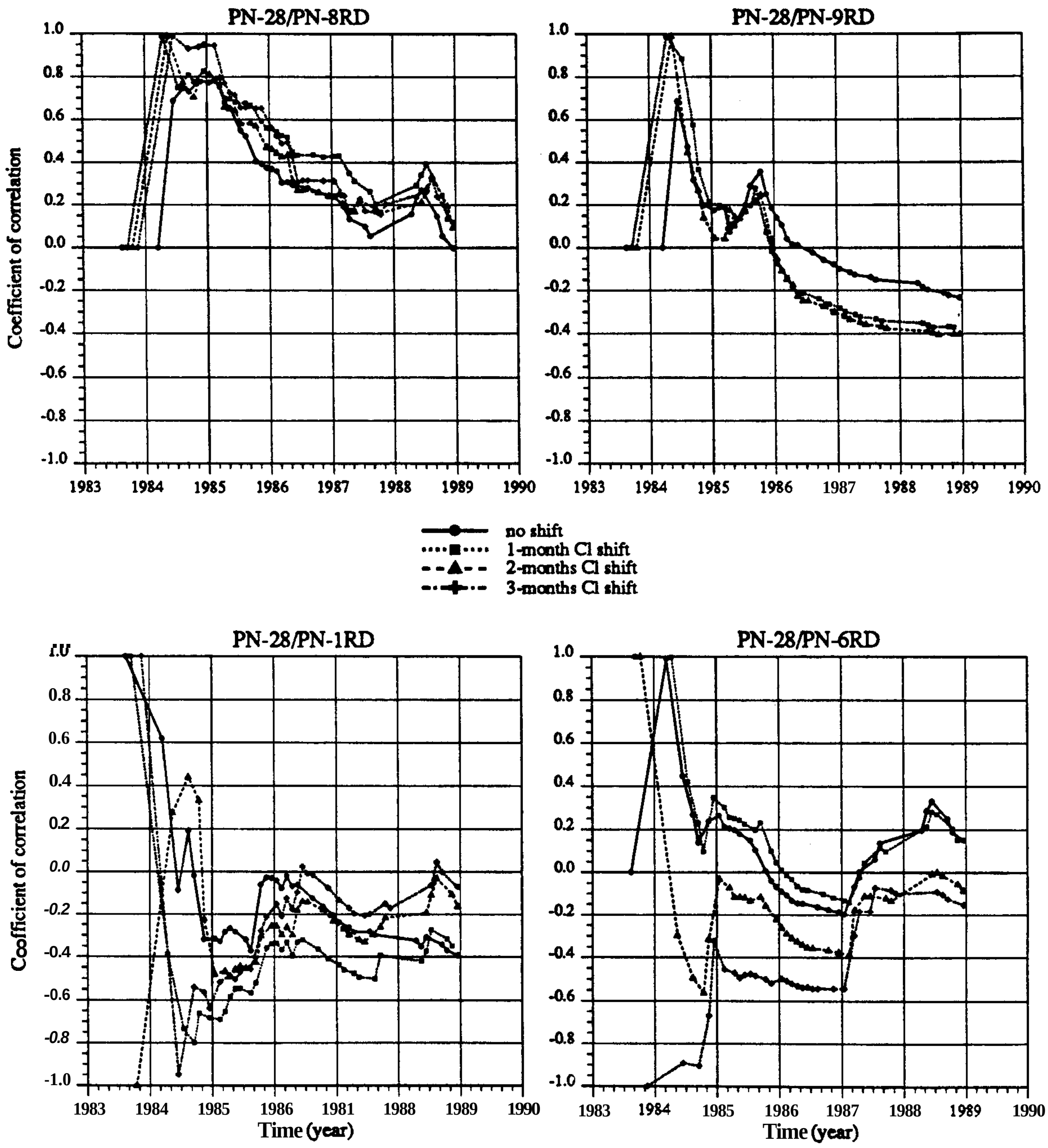


Figure *G.5:* PN-28 chloride shift-flow correlation

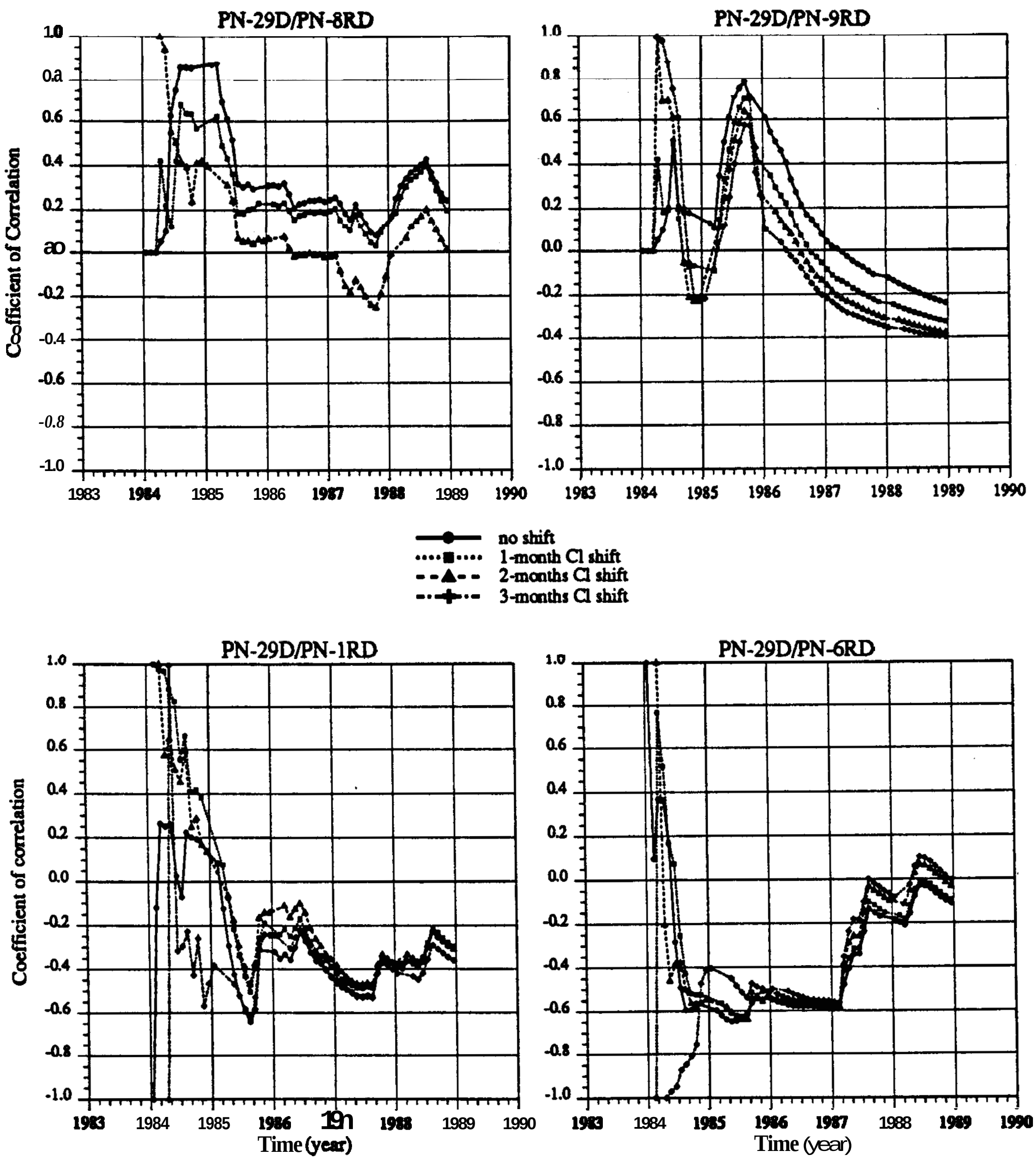


Figure *G.6:* PN-29D chloride shift-flow correlation

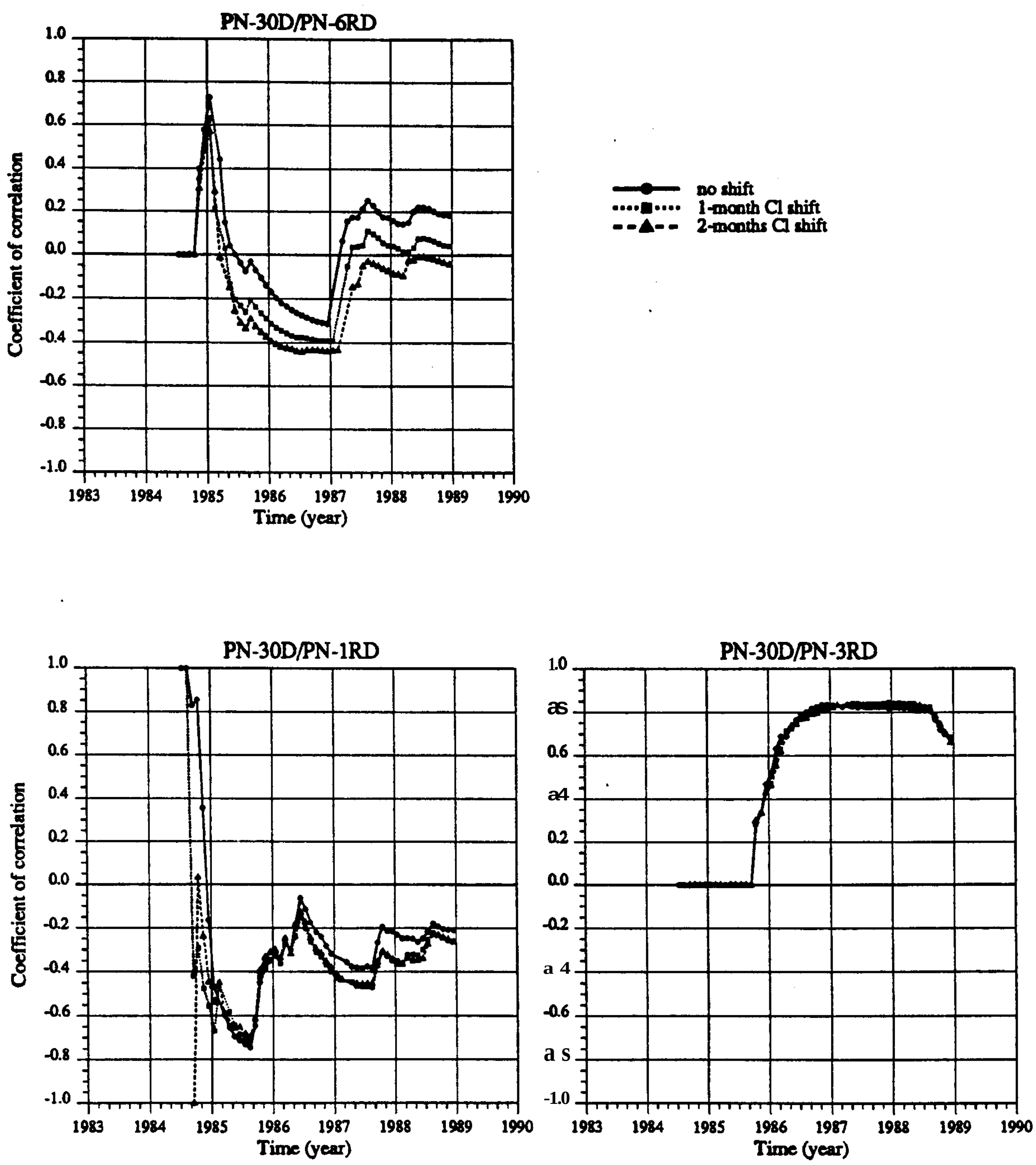


Figure G.7: PN-30D chloride shift-flow correlation

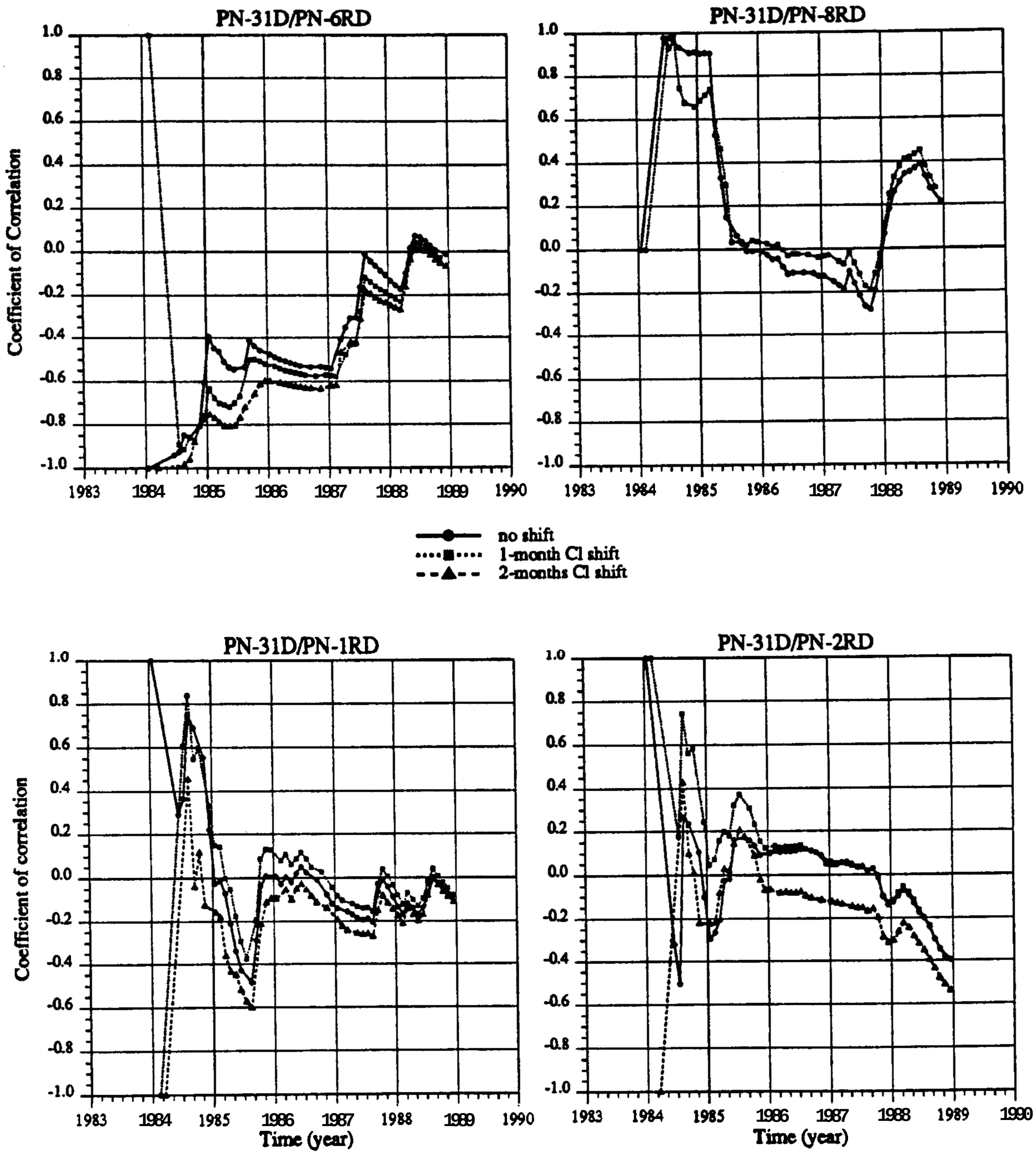


Figure *G.8:* **PN-31D chloride shift-flow correlation**

Appendix H

Chloride-Cumulative Flow Correlation

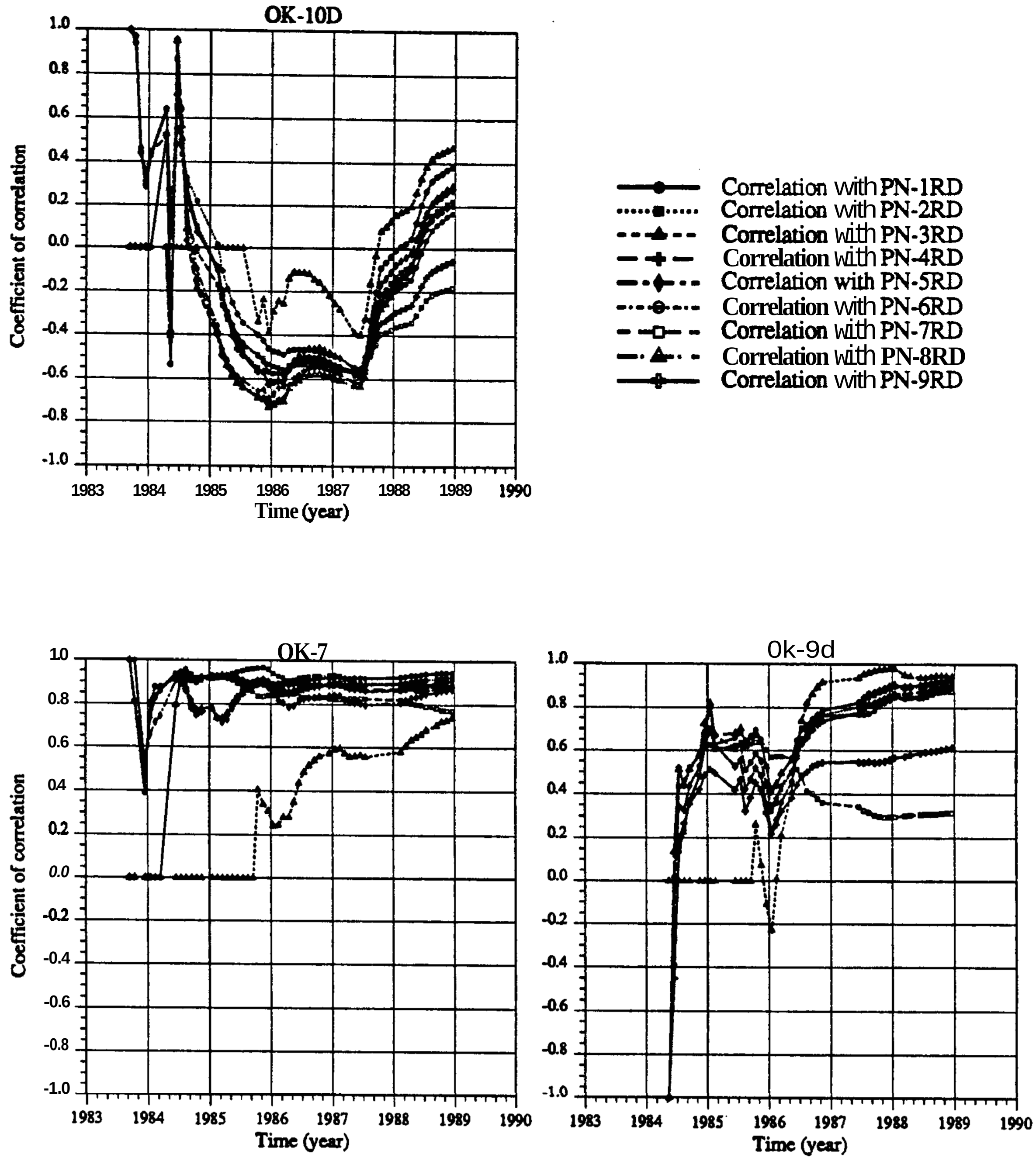


Figure H.1: **Chloride-cumulative flow correlation.**

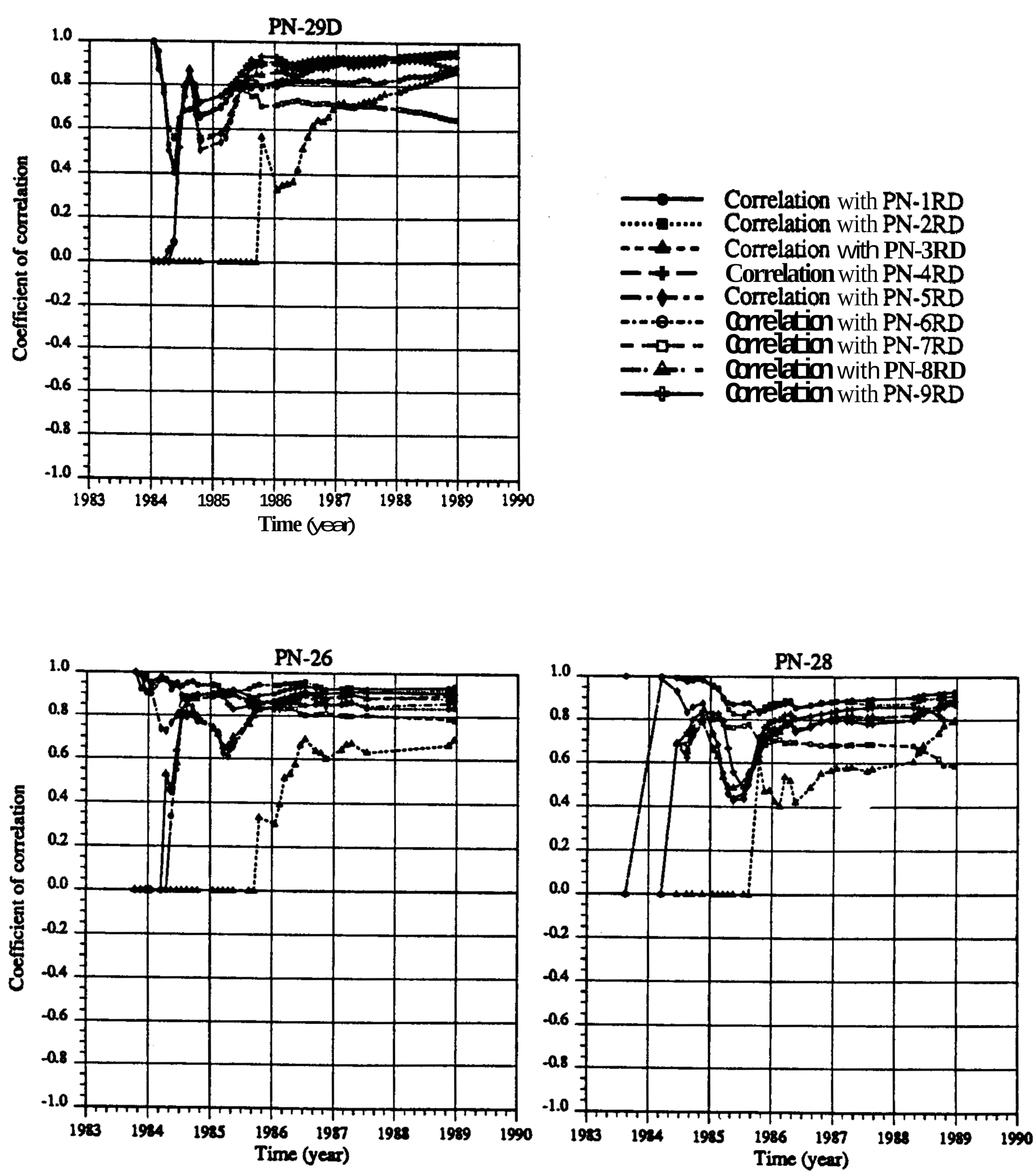


Figure H.2: Chloride-cumulative flow correlation.

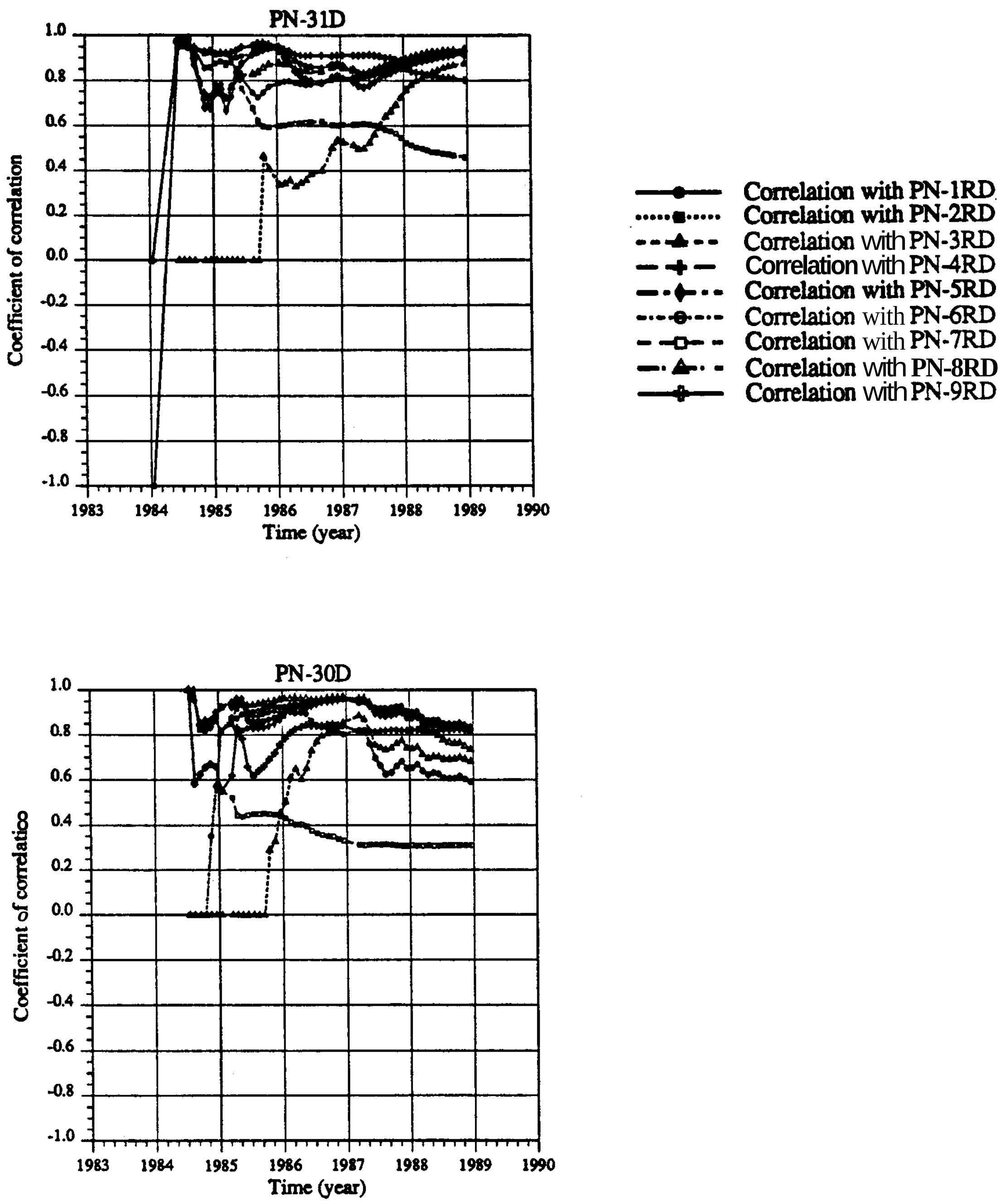


Figure H.3: Chloride-cumulative flow correlation.

Appendix I

Chloride Deviation-Flow Correlation

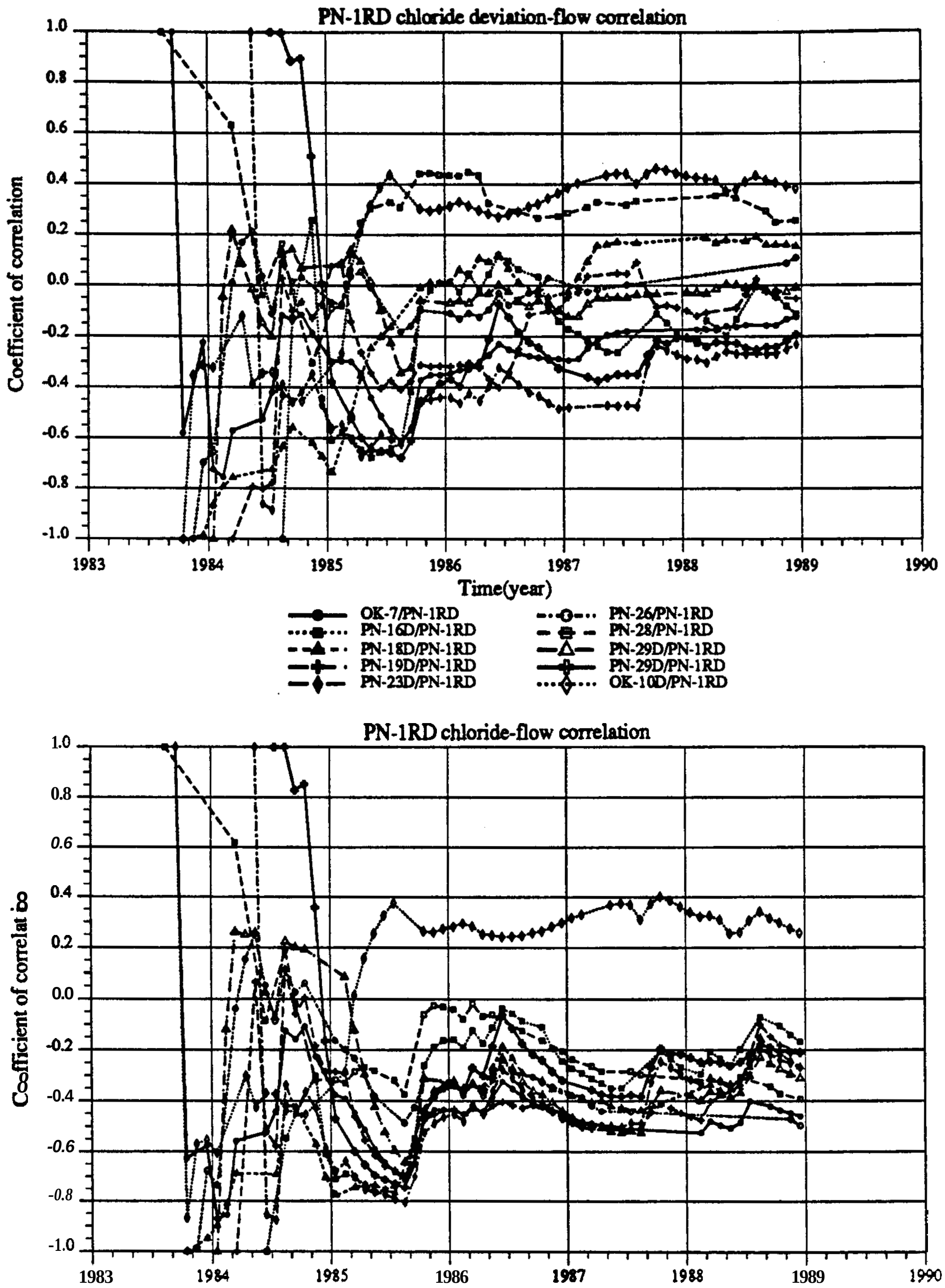


Figure 1.1: PN-1RD Chloride deviation-flowrate correlation.

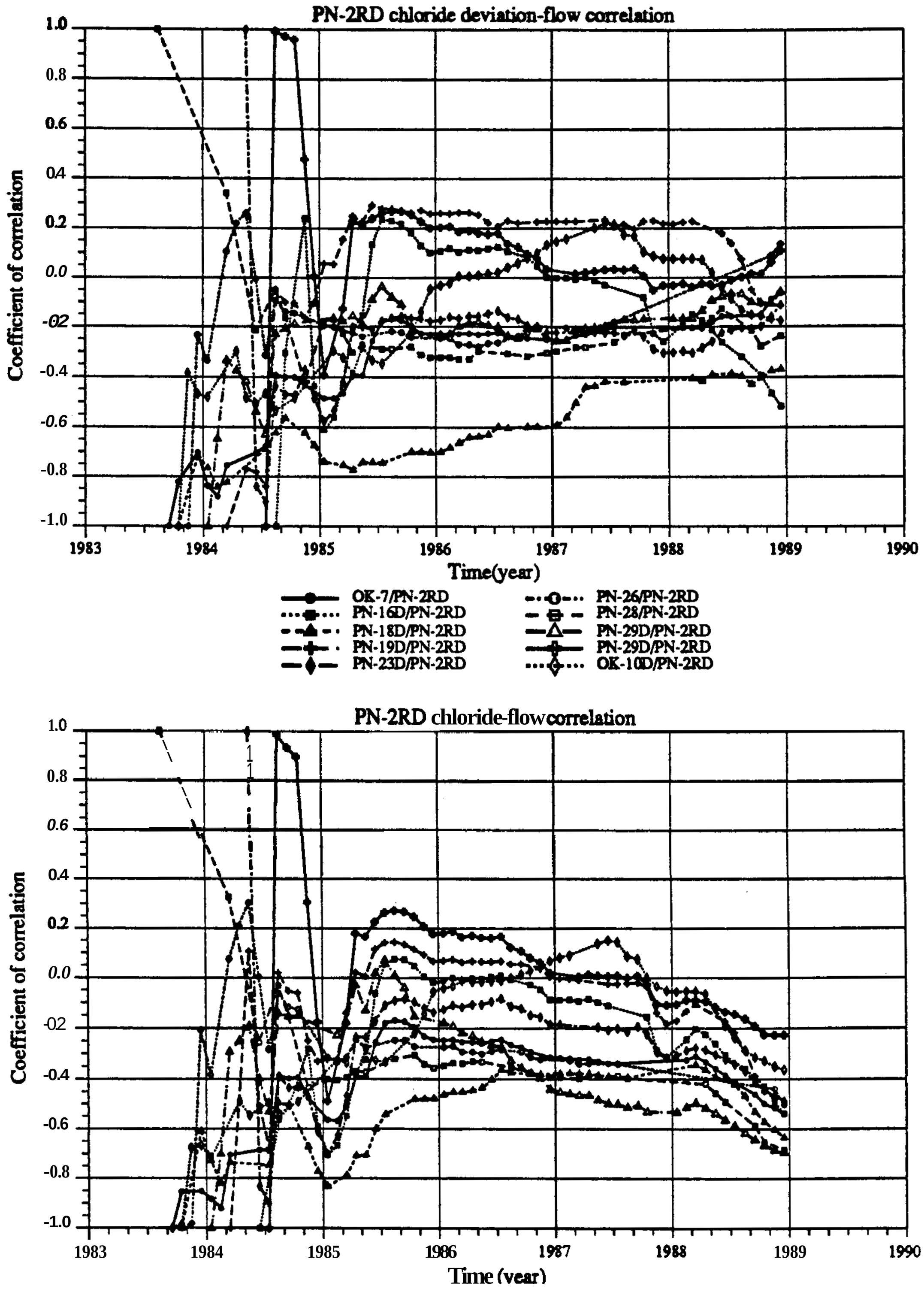


Figure 1.2: PN-2RD Chloride deviation-flowrate correlation.

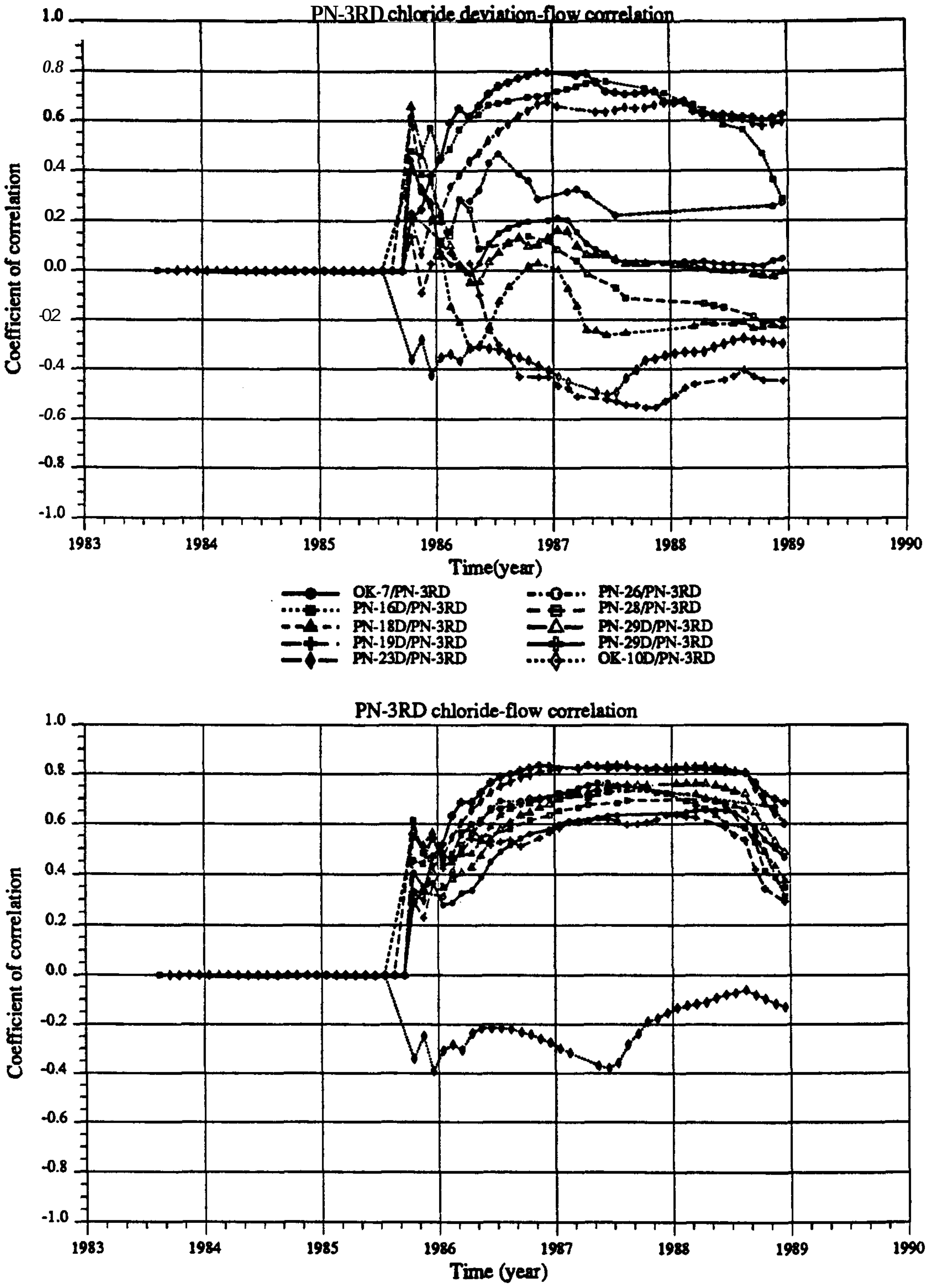


Figure I.3: PN-3RD Chloride deviation-flowrate correlation.

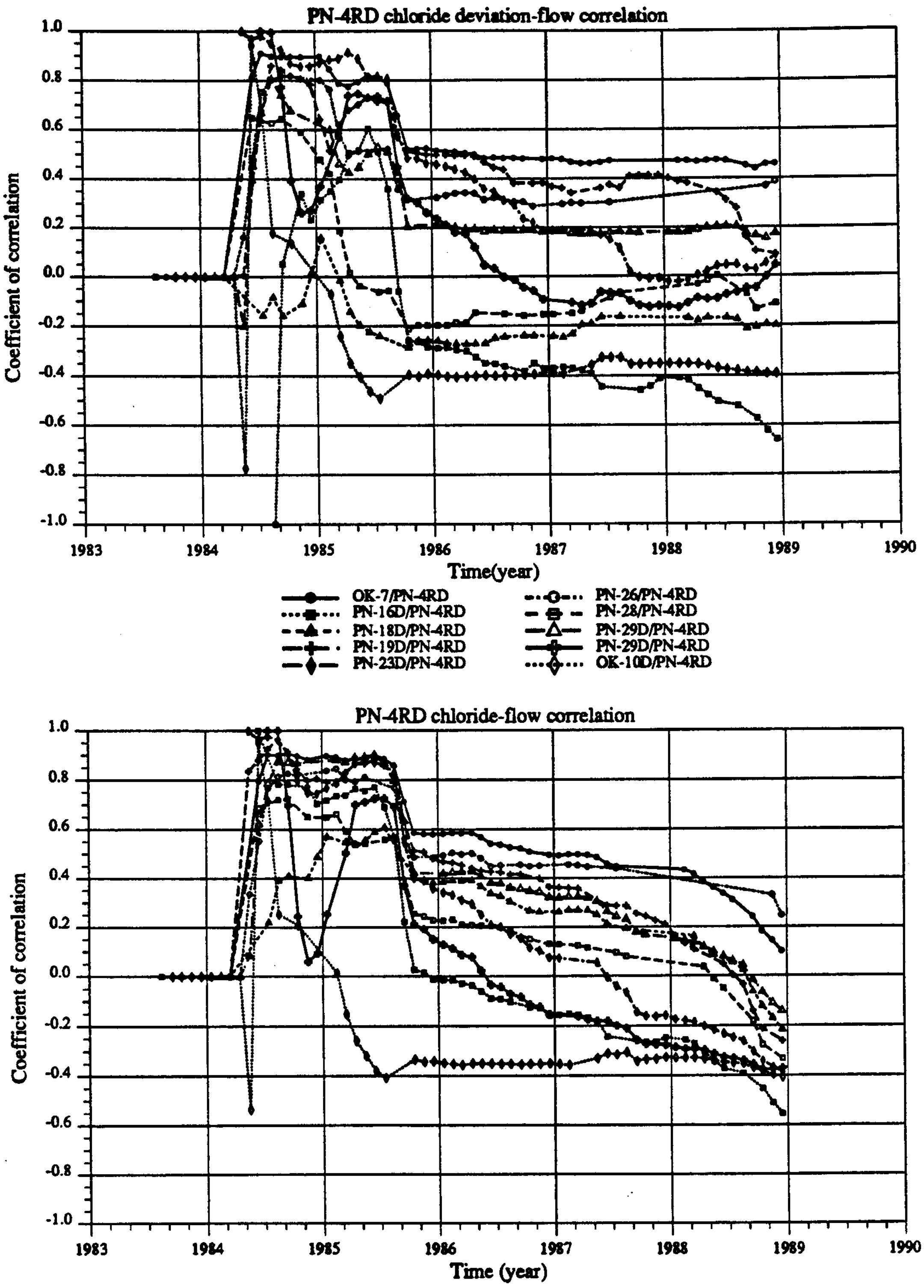


Figure I.4: PN-4RD Chloride deviation-flowrate correlation.

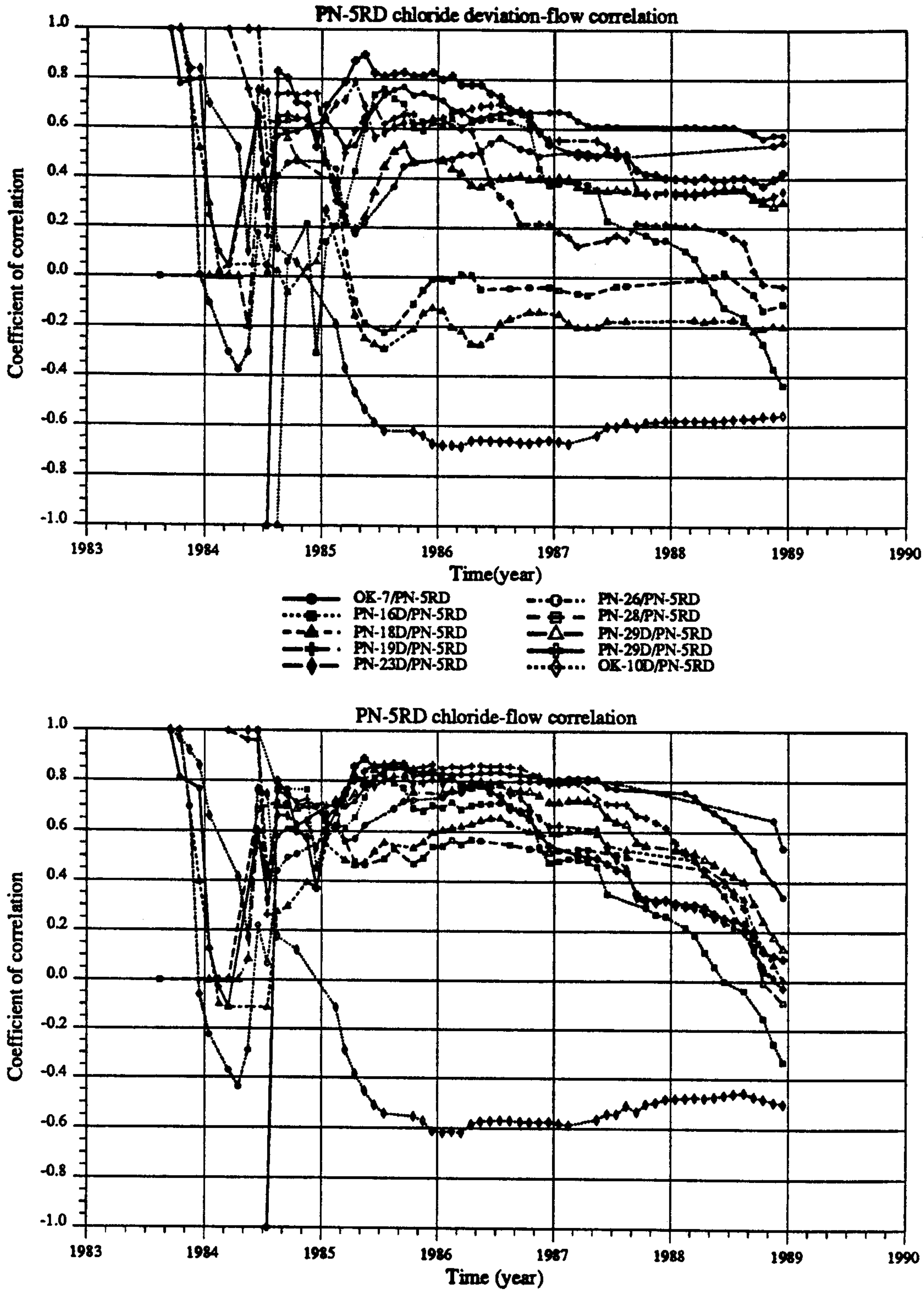


Figure I.5: PN-5RD Chloride deviation-flowrate correlation.

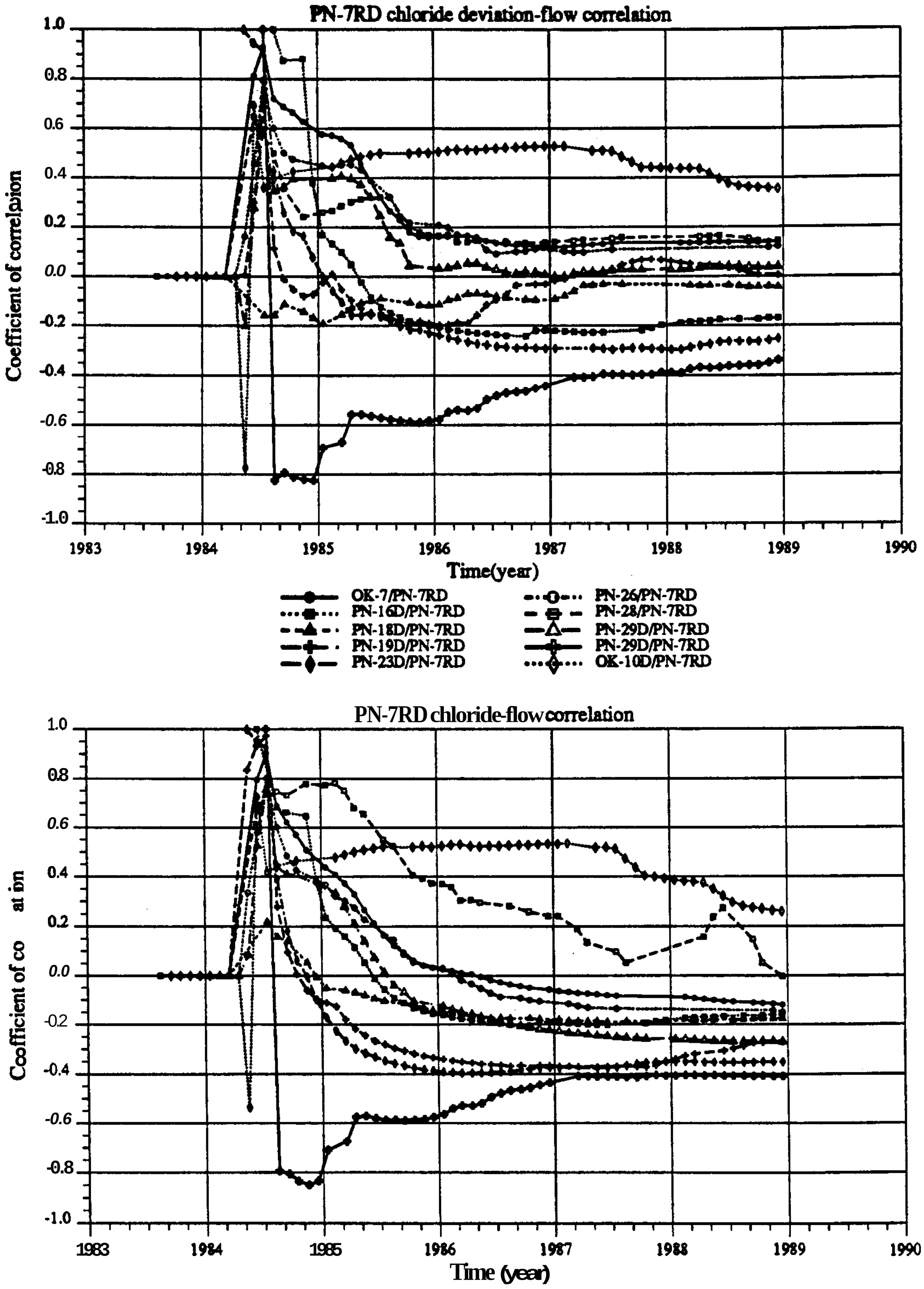


Figure 1.6: PN-7RD Chloride deviation-flowrate correlation.

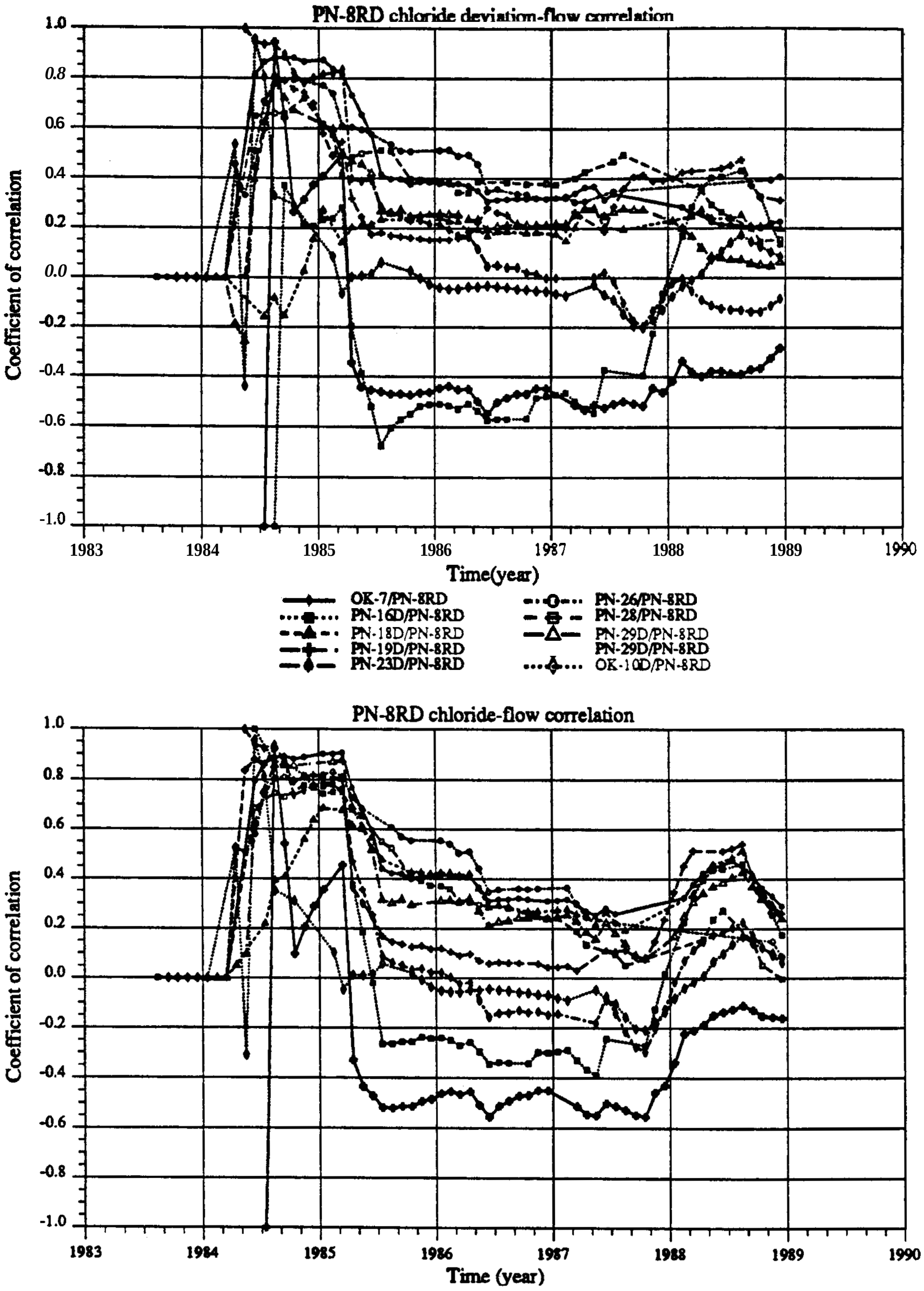


Figure I.7: PN-8RD Chloride deviation-flowrate correlation.

Appendix J

Chloride Deviation-Flow Program Code

```
c  This program aims to find the correlation coefficient (r) between a
c  production well's Chloride residual or deviation from the best fit
c  line and an injection well's flow rate with time.
      program rescorr
      implicit real*8 (a-h, o-z)
      dimension tprod(200), tinj(200), dev(200), flow(200)
      dimension data1(200), data2(200), data3(200)
      dimension dummy1(200), dummy2(200), dummy3(200)
      character*15 infilel, infile2, outfile, pltfile
      character*6 prodwell, injwell
      write (6,101 ' Input file name 1 (Preg.plt)     : '
10    format (a,$)
      read (5,201 infilel
15    format (a6)
20    format (a15)
      write (6,101 ' Input file name 2 (Rinj.dat)     : '
      read (5,201 infile2
      write (6,101 ' Output file name (P-Rdev.cor)  : '
      read (5,201 outfile
      write (6,101 ' Plot file name (P-Rdev.plt)    : '
      read (5,201 pltfile
      write (6,101 ' Production well                . '
      read (5,151 prodwell
      write (6,101 ' Injection well                 . '
      read (5,151 injwell
      write (6,101 ' Lag time in months             . '
      read (5,251 nt
25    format (i2)
      open (unit-1,status='old',file=infilel)
      open (unit=2,status='old',file=infile2)
      open (unit=3,status='unknown',file=outfile)
      open (unit=4,status='unknown',file=pltfile)
      nprod = 1
```

```
30      read (1,*,end=100) tprod(nprod),dev(nprod)
        nprod = nprod + 1
        goto 30
100     nprod = nprod - 1
        ninj  = 1
40      read (2,*,end=200) tinj(ninj), flow(ninj)
        ninj  = ninj + 1
        goto 40
200     ninj  = ninj - 1
        k = 1
        i = 1
210     if ( i .gt. nprod ) goto 350
        j = 1
220     if (tprod(i) .eq. tinj(j)) then
          dummy1(k) = tprod(i)
          dummy2(k) = dev(i)
          dummy3(k) = flow(j)
          k = k + 1
          i = i+1
          goto 210
        else
          j = j + 1
          if ( j .gt. ninj ) then
            i = i + 1
            goto 210
          endif
          goto 220
        endif
350     ndata = k-1
        nn = nt + 1
        i = 1
        do 400 k= nn, ndata
          if ( dummy2(k-nt) .ge. 1.E10 ) goto 400
```

```
          data1(i) = dummy1(k)
          data2(i) = dummy2(k-nt)
          data3(i) = dummy3(k)
          i = i + 1
400     continue
        ndata = i - 1
        write (3,401)
401     format (' ')
        write (3,402)
402     format (' ')
        write (3,403)
403     format (' ')
        write (3,404) prodwell, injwell,nt
404     format (' ',10x,a6, '/',a6, ' Cldev-Flow CORRELATION with LAG of',
     &  i2, ' MONTH(S)')
        write (3,405)
405     format (' ',10x, '---------------------------------------------',
     &  '--------------')
        write (3,406)
406     format (' ')
        write (3,407) 'TIME','R' ,'R**2','Sx','Sy'
407     format (' ',5x,a4,10x,a,9x,a4,11x,a2,14x,a2)
        mdata = ndata-1
        write (4,410) mdata
410     format (i3)
        do 420 i = 2,ndata
        call coeff (i,data2,data3,r,r2,sx,sy)
        write (3,412) data1(i), r, r2, sx, sy
412     format (2x,f10.4,2x,f10.6,2x,f10.6,2f15.5)
        write (4,415) data1(i), r
415     format (f10.4,1x,f10.6)
420     continue
        close (unit=1)
```

```
      close (unit-2)
      close (unit-3)
      end
c
c
      subroutine coeff ( n, data2, data3, r, r2, sx, sy )
      implicit real*8 (a-h, o-z)
      dimension data2(200), data3(200)
      devsum = 0.
      flowsum = 0.
      sqdevsum = 0.
      sqflowsum = 0.
      sumdevflow = 0.
      do 10 i = 1,n
      devsum   = devsum + data2(i)
      flowsum = flowsum + data3(i)
      sqdevsum = sqdevsum + data2(i)*data2(i)
      sqflowsum = sqflowsum + data3(i)*data3(i)
      sumdevflow = sumdevflow + data2(i)*data3(i)
10    continue
      if (flowsum .eq. 0.0) goto 99
      xn   =  real(n)
      xbar = devsum/xn
      ybar = flowsum/xn
      syl = (sqflowsum - flowsum*flowsum/xn)/xn
      sy  = sqrt(sy1)
      if (sy .eq. 0.0) return
      sx1 = (sqdevsum - devsum*devsum/xn)/xn
      sx  = sqrt(sx1)
      r   = (sumdevflow - xn*xbar*ybar)/(xn*sx*sy)
      r2  = r*r
99    return
      end
```

Appendix K

Linear Combination Program Code and Output

```
      program lincomb4
c--------------------------------------------------------------------
c   This program computes for the solution of the linear combination
c   method where chloride is expressed as a linear combination of
c   the injection flowrates. The input file tabulates the chloride
c   trend with time of a production well and the flowrates of the
c   injection wells corresponding to the chloride measurements.
c--------------------------------------------------------------------
      implicit real*8 (a-h, o-z)
      dimension a(10,10),rhs(10)
      character*15 filename
      character*8 pname,riname(9)
      dimension flow(9),need(9),dumflow(9)
c
      do i = 1,10
rhs(i) = 0.
do j = 1,10
  a(i,j) = 0.
        enddo
      enddo
      write (6,10) 'File Name For Calculation (*bal.out)   : '
10    format (a40,$)
      read (5,20) filename
20    format (a15)
      open (unit=1,status='old',file=filename)
      open (unit=2,status='unknown',file='soln.dat')
      read (1,30) pname,nri,(riname(i), i=1,9)
30    format (a8,1x,i2,9(1x,a8))
      write (6,40) 'Available Reinjection Wells are : '
40    format (10x,a35)
      do i = 1,nri
write (6,50) i, riname(i)
50      format (i2,5x,a8)
```

```
      enddo
55    write (6,60) 'Number of wells to be included in computation'
60    format (a46)
      write (6,70) '(min = 1, max = 9) : '
70    format (a21, $)
      read (5,80) nwells
80    format (i3)
      if (nwells .lt. 1 .or. nwells .gt. 9) goto 55
      if (nwells .eq. 9) then
do i = 1,9
  need(i) = i
        enddo
goto 105
      endif
      write (6,90) 'Type the number corresponding to the wells needed'
90    format (a50)
      do i = 1,nwells
        read(5,100) need(i)
100   format (i2)
      enddo
105   write (6,110) 'Time interval needed in computation : '
110   format (a38)
      write (6,120) 'Tmin : '
120   format (a7,$)
      read (5,130) tmin
130   format (f10.4)
      write (6,120) 'Tmax : '
      read (5,130) tmax
      write (2,140) 'Production Well                        : ',pname
140   format (a40,a8)
      write (2,150) 'Number of Reinjection Wells Included : ',nwells
150   format (a40,i2)
      do i = 1,nwells
```

```
          write (2,160) i,riname(need(i))
160       format (10x,i1,5x,a8)
        enddo
        write (2,170) 'Time Interval Considered             . '
170     format (a40)
        write (2,180) 'Tmin = ',tmin
        write (2,180) 'Tmax = ',tmax
180     format (10x,a7,f10.4)
        kp = 1
200     read (1,210,end=1000) time,cl,(flow(i), i=1,nri)
        if (kp.eq.1) cl0 = cl
210     format (f10.4,2x,f6.0,9f8.2)
        if ( time .lt. tmin .or. time .gt. tmax ) goto 200
        do i = 1,nwells
 if (flow(need(i)) .eq. -99.) goto 200
 dumflow(i) = flow(need(i))
        enddo
        nromax = nwells + 1
        do i = 2,nromax
a(1,i) = a(1,i) + dumflow(i-1)
a(i,1) = a(i,1) + dumflow(i-1)
do j = 2,nromax
  a(j,i) = a(j,i) + dumflow(i-1)*dumflow(j-1)
          enddo
        enddo
        rhs(1) = rhs(1) + cl
        do i = 2,nromax
rhs(i) = rhs(i) + dumflow(i-1)*cl
        enddo
        kp = kp + 1
        goto 200
1000    p = kp - 1
c       a(1,1) = p
```

```
      a(1,1) = 1.0
      do 77 i=2,10
 77   a(1,i)=0.
      rhs(1)= c10
      call matrix (a,rhs,nromax)
      end
c
c----------------------------------------------------------------------
      subroutine matrix (a,y,size)
c
      implicit real*8 (a-h, o-z)
      logical error
      integer size
      dimension a(10,10),y(10),b(10,10),coef(10),index(10,3)
c
      nvec = 1
      maxr = 10
      maxc = 10
      write (2,5)
5     format ('-----------------------------------------------------------
     &--------------------')
      write (2,10) 'Simultaneuos solution by Gauss-Jordan Elimination'
10    format (20x,a50)
      write (2,5)
      do i = 1,size
 do j = 1,size
   b(i,j) = a(i,j)
          enddo
          coef(i) = y(i)
      enddo
      call gaussj (b,coef,index,size,maxc,nvec,error)
      if ( .not. error ) then
       write (2,15) 'Matrix A     : ',size,'x',size
```

```
15      format (a15,i2,1x,a1,1x,i2)
        do i = 1,size
          write (2,20) (a(i,j), j=1,size)
20        format (10(1x,e10.4))
        enddo
        write (2,25) 'Right Hand Side : '
        write (2,27) (y(i), i=1,size)
25      format (a18)
27      format (10(1x,e10.4))
        write (2,30)
30      format ('------------------------------ solution ---------------
     &---------------')
        write (2,35) 'Coefficients : '
35      format (a15)
        write (2,40) (coef(i) , i=1,size)
40      format (10(1x,e10.4))
        return
      endif
      write (2,50)
50    format ('!!!!!!!!!!!!!! No Solution !!!!!!!!!!!!!!')
      return
      end
c
c-----------------------------------------------------------------------
      subroutine gaussj (b,w,index,nrow,max,nvec,error)
c
      implicit real*8 (a-h, o-z)
      logical error
      dimension b(max,1),w(max,1),index(max,3)
c
      error = .false.
      do i = 1,nrow
index(i,3) = 0
```

```
      enddo
      determ = 1.0
      do i = 1,nrow
big = 0.0
do j = 1,nrow
   if (index(j,3) .eq. 1) goto 20
   do k = 1,nrow
     if (index(k,3) .gt. 1) goto 199
     if (index(k,3) .eq. 1) goto 15
     if (abs(b(j,k)) .le. big ) goto 15
irow = j
icol = k
big = abs(b(j,k))
15          enddo
20       enddo
index(icol,3) = index(icol,3) + 1
index(i,1) = irow
index(i,2) = icol
if (irow .eq. icol) goto 40
        determ = -1*determ
        do 1 = 1,nrow
          call swap(b(irow,l),b(icol,l))
25       enddo
if (nvec .eq. 0) goto 40
do 1 = 1,nvec
  call swap(w(irow,l),w(icol,l))
30       enddo
40       pivot = b(icol,icol)
determ = determ*pivot
b(icol,icol) = 1.0
do 1 = 1,nrow
   b(icol,l) = b(icol,l)/pivot
45       enddo
```

```
if (nvec .eq. 0) goto 60
do 1 = 1,nvec
   w(icol,l) = w(icol,l)/pivot
50       enddo
60       do 11 = 1,nrow
   if (l1 .eq. icol) goto 80
   t = b(l1,icol)
   b(l1,icol) = 0.0
   do 1 =1,nrow
      b(l1,l) = b(l1,l) - b(icol,l)*t
65          enddo
   if (nvec .eq. 0) goto 80
   do 1 = 1,nvec
      w(l1,l) = w(l1,l) - w(icol,l)*t
70          enddo
80        enddo
90     enddo
      do i = 1,nrow
 l = nrow - i + 1
 if (index(l,1) .eq. index(l,2)) goto 120
    irow = index(l,1)
    icol = index(l,2)
    do k = 1,nrow
       call swap(b(k,irow),b(k,icol))
110         enddo
120   enddo
      do k = 1,nrow
if (index(k,3) .ne. 1) goto 199
130   enddo
      return
199   write (2,999)
      error = .true.
      return
```

```
999   format (' error -- matrix singular ')
      end
c
c--------------------------------------------------------------
      subroutine swap(a,b)
c
      implicit real*8 (a-h, o-z)
c
      hold = a
      a    = b
      b    = hold
      return
      end
```

```
************************************************************

This is a sample output of the program lincomb4.f

**************************************************************


Production Well                        : OK-7
Number of Reinjection Wells Included :  3
         1     PN-1RD
         2     PN-2RD
         3     PN-6RD
Time Interval Considered
         Tmin =   1983.6219
         Tmax =   1984.1233
............................................................
         Simultaneuos solution by Gauss-Jordan Elimination
............................................................
Matrix A      :  4 x  4
 0.1000E+01 0.0000E+00 0.0000E+00 0.0000E+00
 0.3820E+03 0.2730E+05 0.1330E+05 0.1155E+05
 0.1912E+03 0.1330E+05 0.6626E+04 0.6112E+04
 0.2395E+03 0.1155E+05 0.6112E+04 0.1468E+05
Right Hand Side :
 0.4298E+04 0.1768E+07 0.8867E+06 0.1174E+07
......................    solution ..........................
Coefficients :
 0.4298E+04 0.5104E+01 -.9489E+01 0.9783E+01
```

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